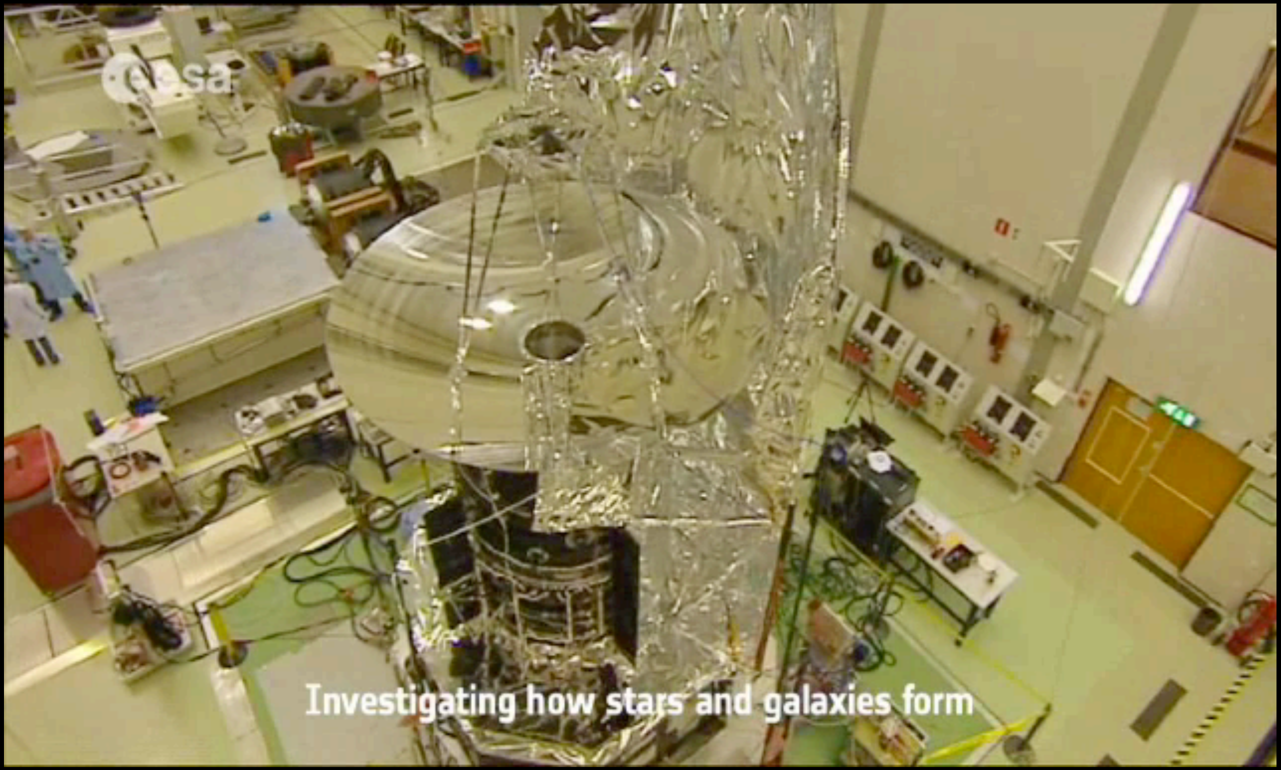
Dusty Universe Mapped by Herschel and CIB in arcminute-scale CMB (and TIME-Pilot to JCMT)

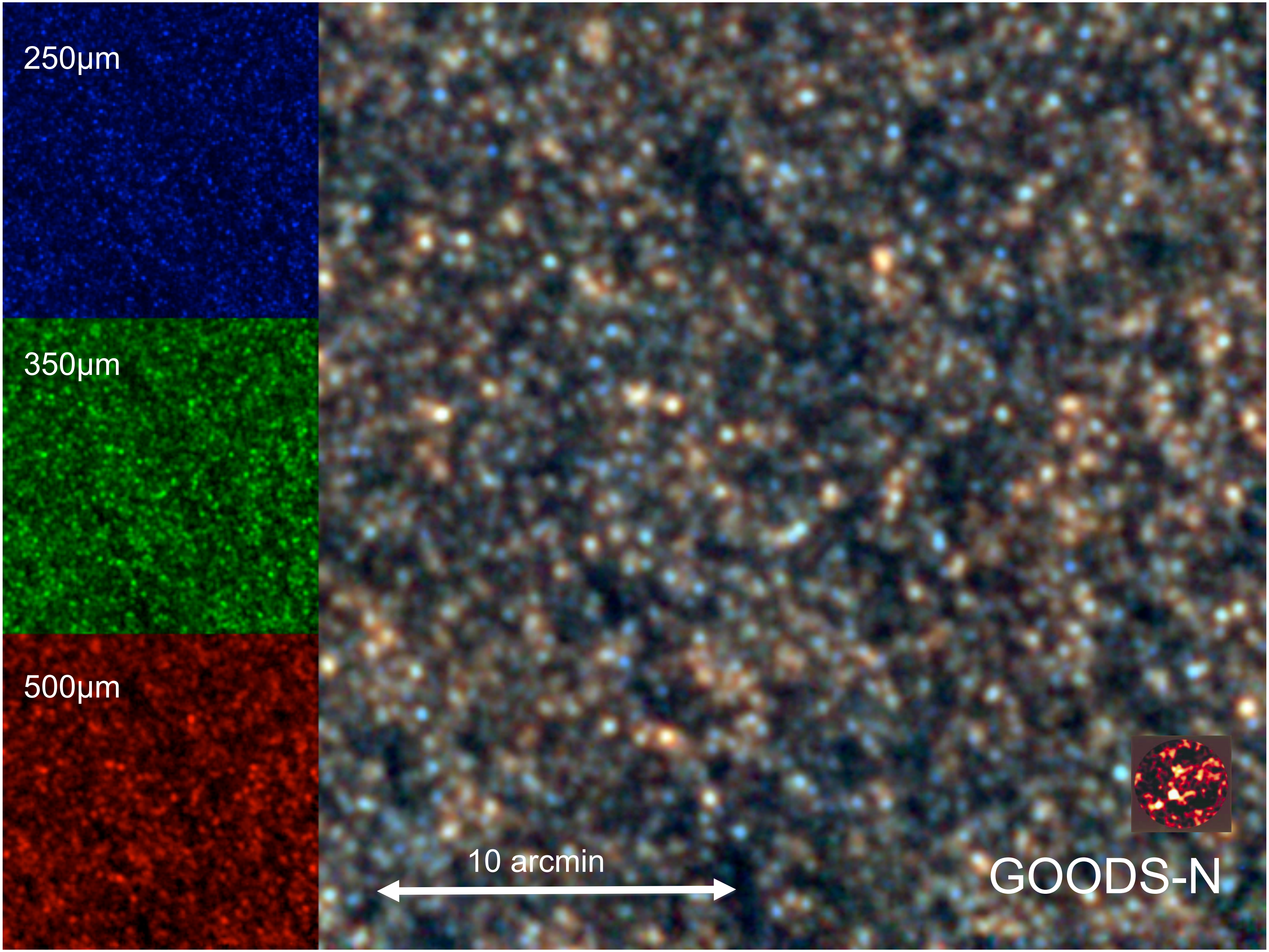


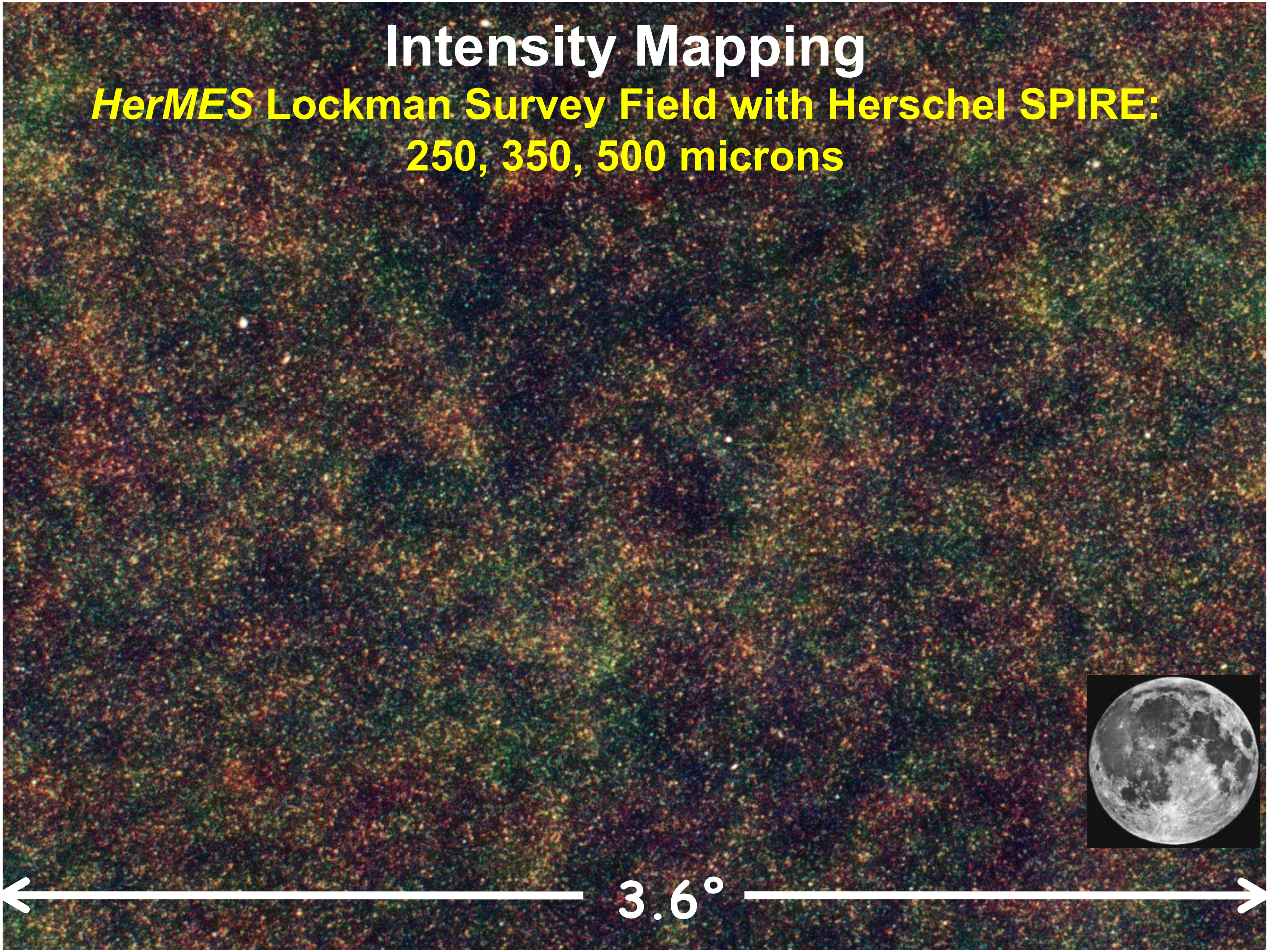
HERMES

ATLAS

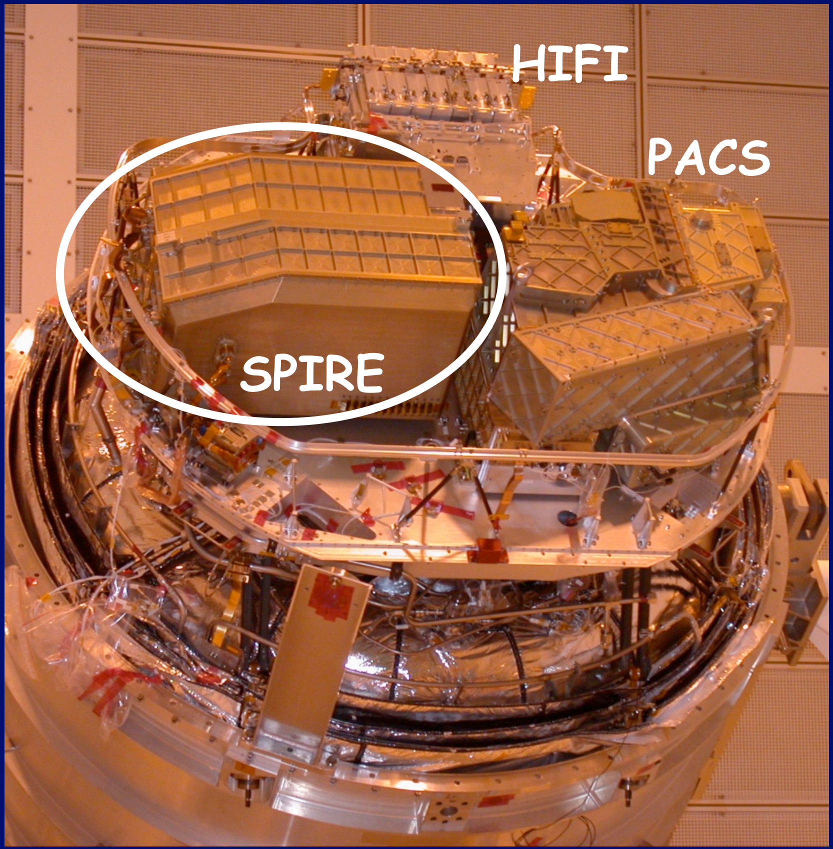
Asantha Cooray

UCIrvine
University of California, Irvine


250µm
350µm
500µm
10 arcmin
GOODS-N


Intensity Mapping
HerMES Lockman Survey Field with Herschel SPIRE:
250, 350, 500 microns
3.6°

SPECTRAL AND PHOTOMETRIC IMAGING RECEIVER



PHOTOMETER

- **250, 350, 500 μm (simultaneous)**
- **4 x 8 arcminute field of view**
- **Diffraction limited beams(18, 25, 36")**

Fast scan mapping at long wavelengths

IMAGING FTS

- 200 - 670 μm
- 2.6 arcminute field of view
- $\Delta\nu$ = 1.2 GHz high resolution mode
- $\Delta\nu$ = 25 GHz low resolution mode

Wide instantaneous bandwidth, map making

DESIGN PRINCIPLES

- ^{3}He cooled detector arrays (0.3 K)
- Feedhorn-coupled spider-web bolometers
- Minimal use of mechanisms Beam steering mirror; FTS mirror drive
- Optimized for scan-mapped surveys

HerMES = SPIRE Instrument Team Survey

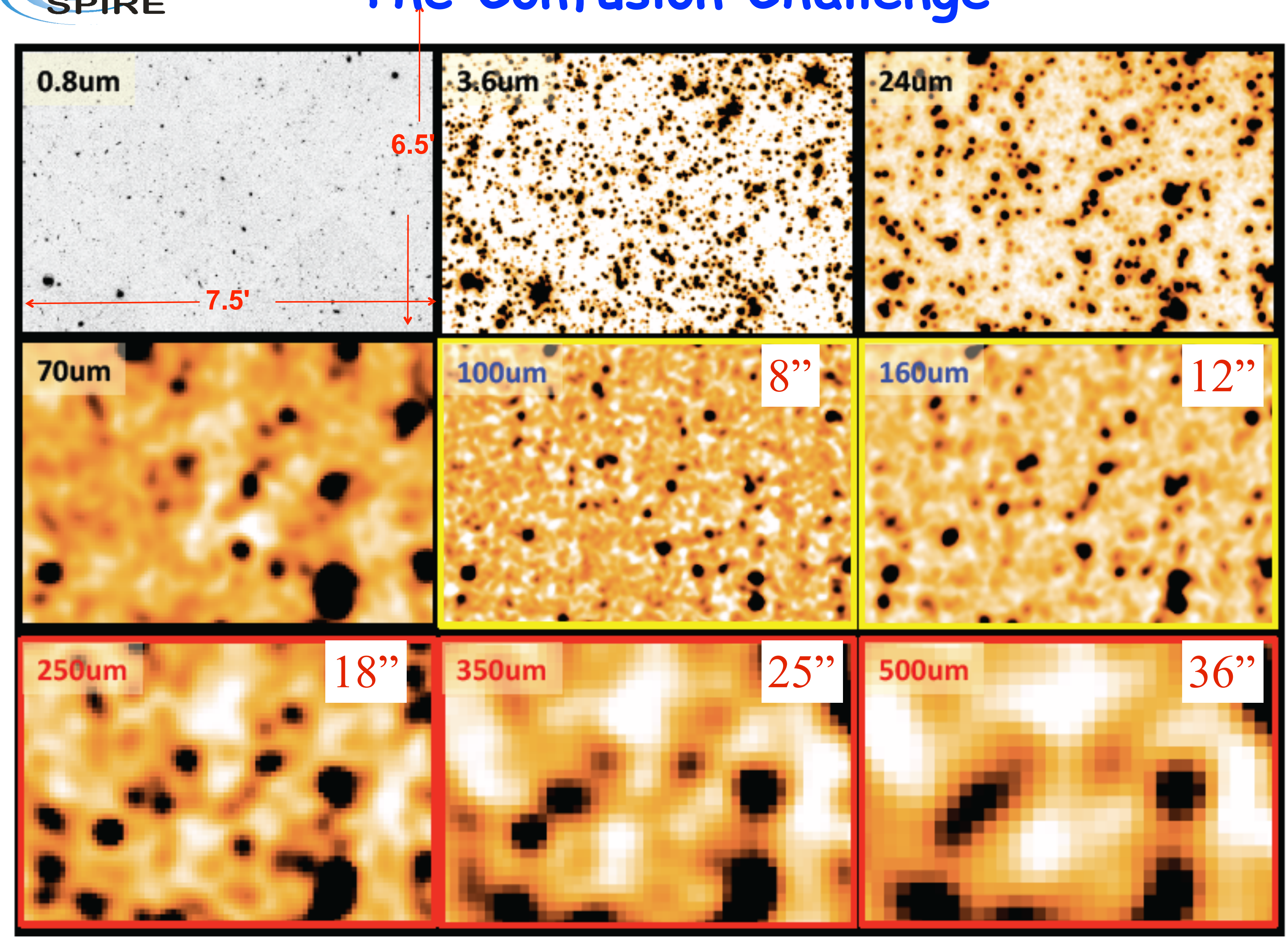
HERMES INFORMATION ON THE WEB: HERMES.SUSSEX.AC.UK AND HERSCHEL.UCI.EDU

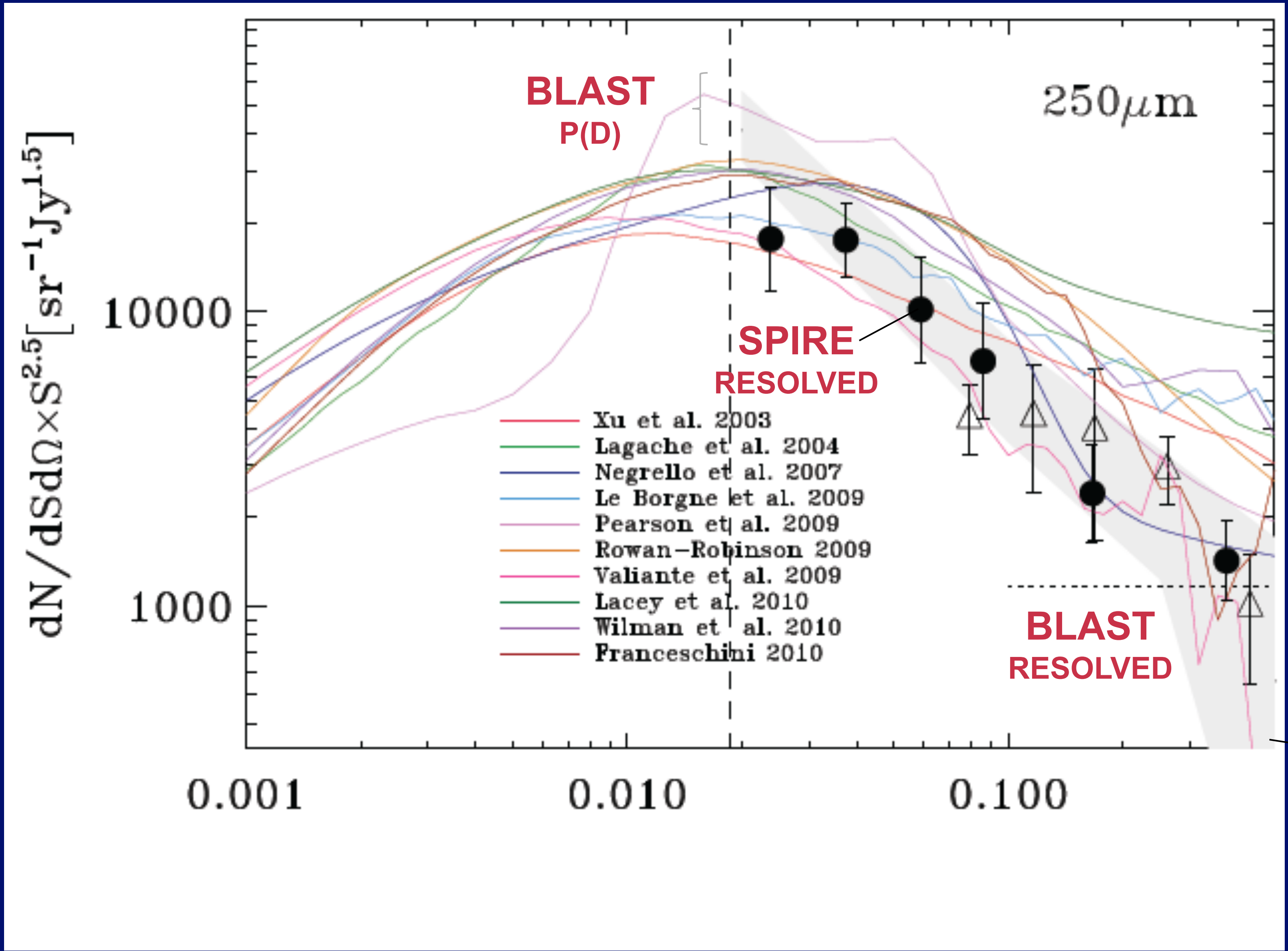
Bruno Altieri, **Alex Amblard**, **Vinod Arumugam**, **Robbie Auld**, Herve Aussel, **Tom Babbedge**, Alexandre Beelen, **Matthieu Bethermin**, Andrew Blain, Jamie Bock, Alessandro Boselli, **Carrie Bridge**, **Drew Brisbin**, Veronique Buat, Denis Burgarella, **Nieves Castro-Rodriguez**, **Antonio Cava**, **Pierre Chanial**, **Ed Chapin**, Scott Chapman, Michele Cirasuolo, Dave Celments, **Alex Conley**, Luca Conversi, Asantha Cooray, Darren Dowell, **Naomi Dubois**, Eli Dwek, **Simon Dye**, Steve Eales, David Elbaz, Duncan Farrah, **Patrizia Ferrero**, **Matt Fox**, Alberto Franceschini, Walter Gear, **Elodie Giovannoli**, Jason Glenn, **Eduardo Gonzalez-Solares**, Matt Griffin, Mark Halpern, Martin Harwit, **Evanthia Hatziminaoglou**, **Sebastian Heinis**, **Peter Hurley**, **HoSeong Hwang**, **Edo Ibar**, **Olivier Ilbert**, Kate Isaak, Rob Ivison, Guilaine Lagache, **Louis Levenson**, Nanyao Lu, Suzanne Madden, Bruno Maffei, **Georgios Magdis**, **Gabriele Mainetti**, Lucia Marchetti, **Gaelen Marsden**, Jason Marshall, **Angela Mortier**, Hien Nguyen, **Brian O'Halloran**, Seb Oliver, Alain Omont, Francois Orieux, Mathew Page, **Pasquale Panuzzo**, **Andreas Papageorgiou**, **Harsit Patel**, **Chris Pearson**, Ismael Perez-Fournon, **Michael Pohlen**, **Jason Rawlings**, **Gwen Raymond**, Dimitra Rigopoulou, **Laurie Riguccini**, **Davide Rizzo**, **Giulia Rodighiero**, **Isaac Roseboom**, Michael Rowan-Robinson, Miguel Sanchez-Portal, Bernhard Schulz, Douglas Scott, **Nick Seymour**, David Shupe, **Anthony Smith**, Jason Stevens,, **Myrto Symeonidis**, **Markos Trichas**, **Katherine Tugwell**, **Mattia Vaccari**, **Elisabetta Valiante**, Ivan Valtchanov, **Joaquin Vieira**, Laurent Vigrouz, **Lingyu Wang**, **Rupert Ward**, **Don Wiebe**, Gillian Wright, Kevin Xu, and **Mike Zemcov**, + *Consultants and Working Members*

FACULTY AND RESEARCHERS, **POSTDOCS**, **STUDENTS**

Herschel-SPIRE Instrument science team

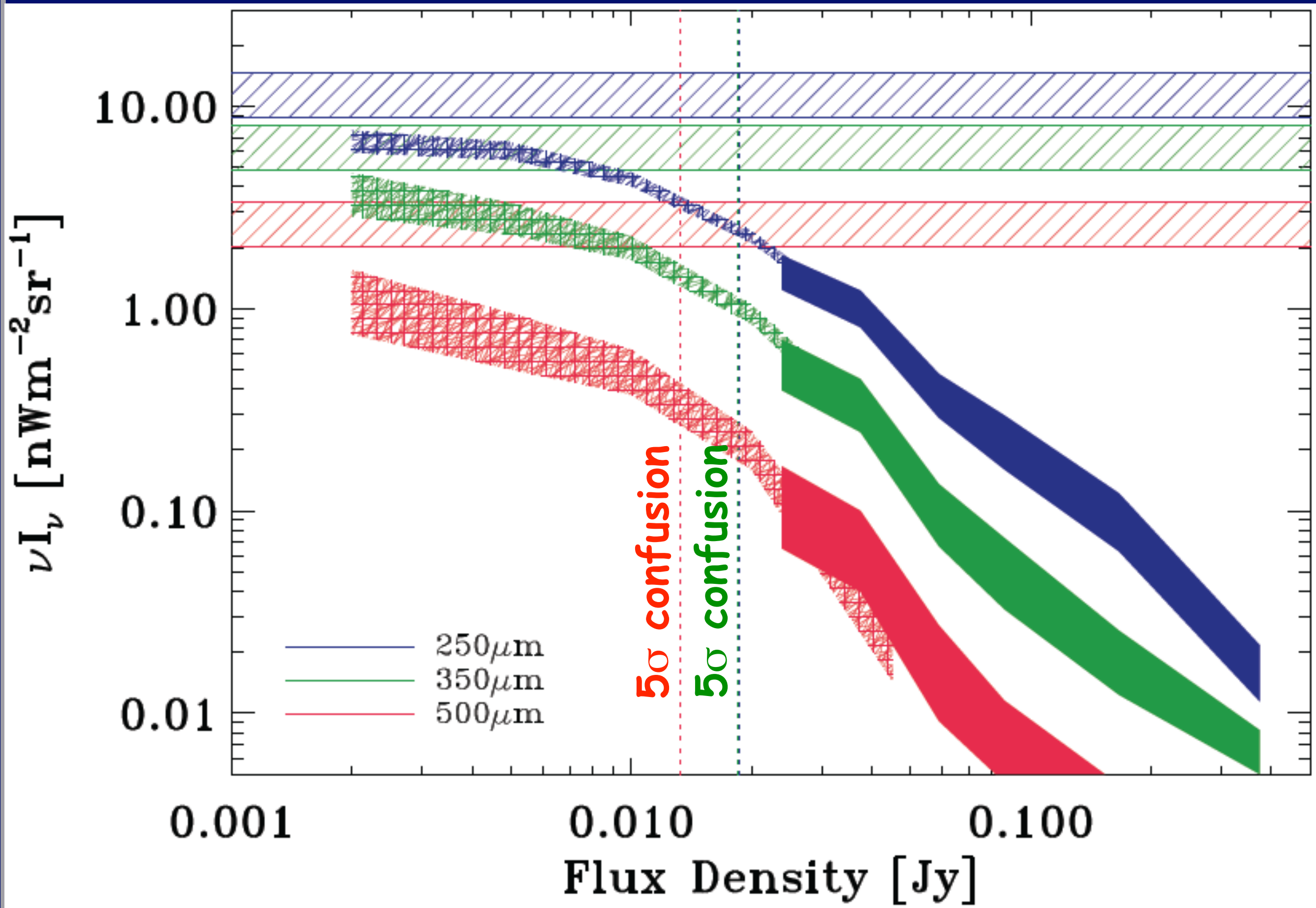
The Confusion Challenge





HerMES-SPIRE Source Counts

HERMES: SPIRE GALAXY NUMBER COUNTS AT 250, 350, AND 500 MM OLIVER ET AL. A&A 518, L21

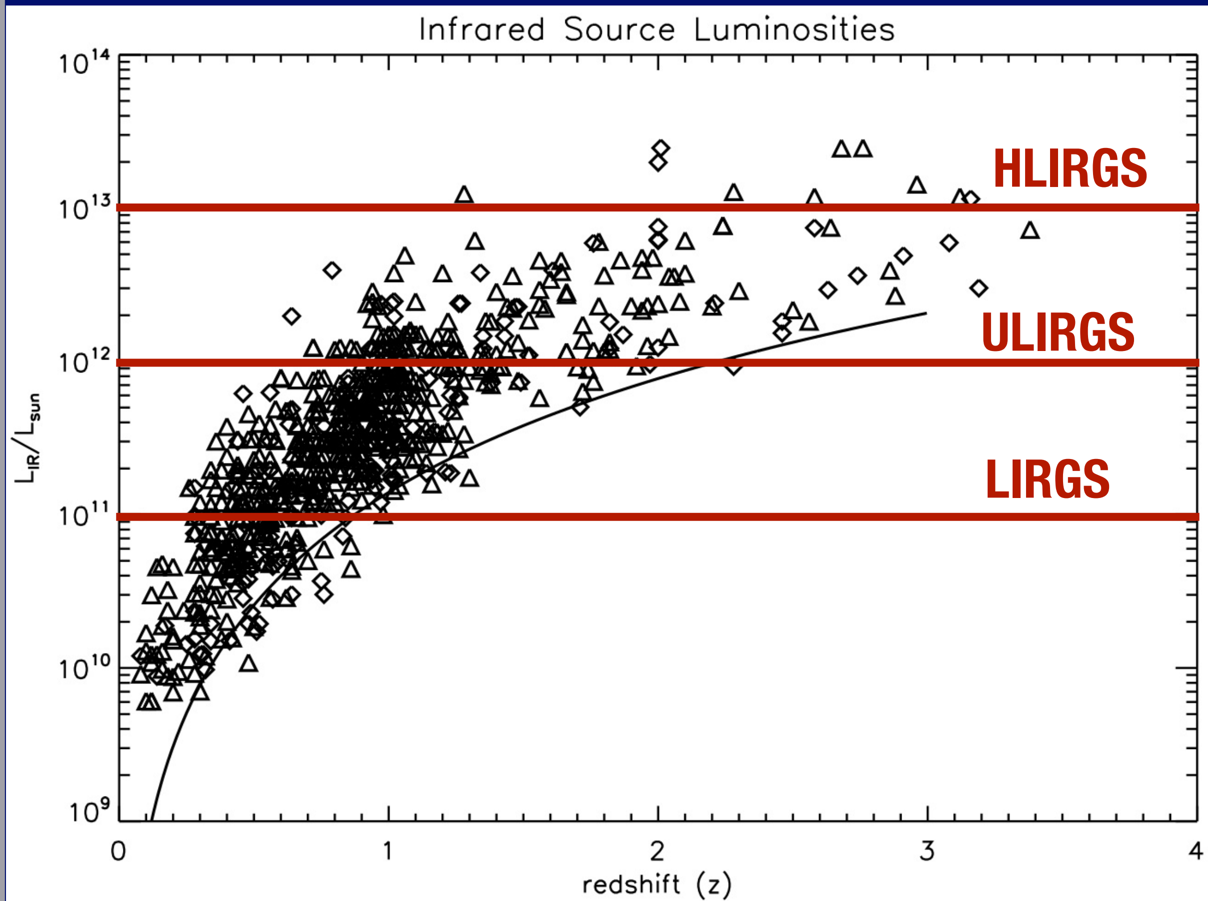


- Source Counts
  250, 350, 500 μm
  15%, 10%, 6%
- P(D)
  250, 350, 500 μm
  65%, 60%, 45%
- Stacking:
  250, 350, 500 μm
  80%, 80%, 85%

Of course: The remainder are the most interesting sources!
E.g. z > 3 galaxy populations

Resolving the Far-IR Background (FIRAS)

HERMES: DEEP GALAXY NUMBER COUNTS FROM P(D) OF SPIRE SDP OBSERVATIONS, GLENN ET AL. 2010, MNRAS 409, 109

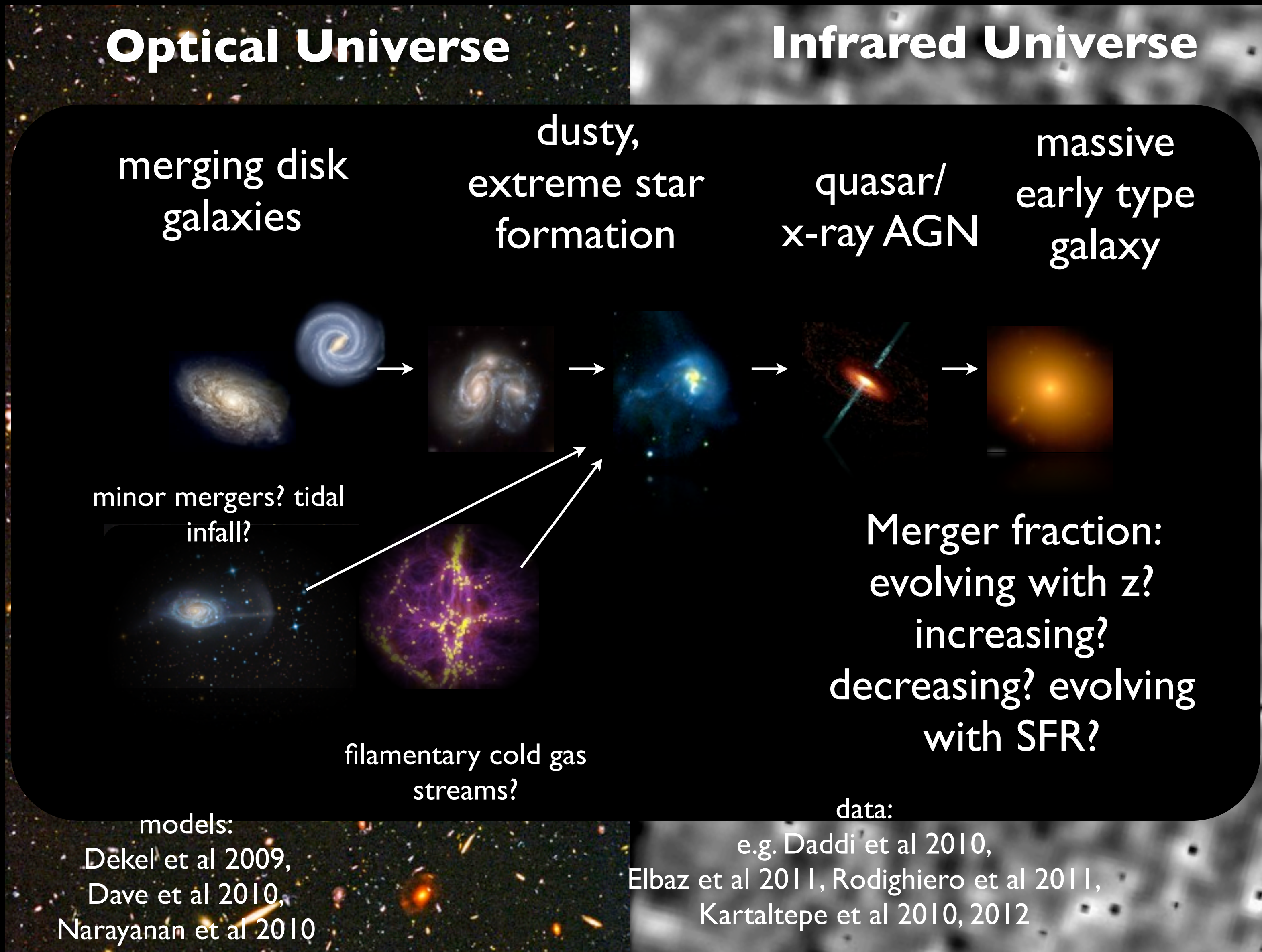


(i) ULIRGS/HyLIRGS typically have about ~10^{10} solar masses in stars

(ii) So the time scale for star-formation is [$M_*/(dM_*/dt)$] ~ 5 to 100 Million years

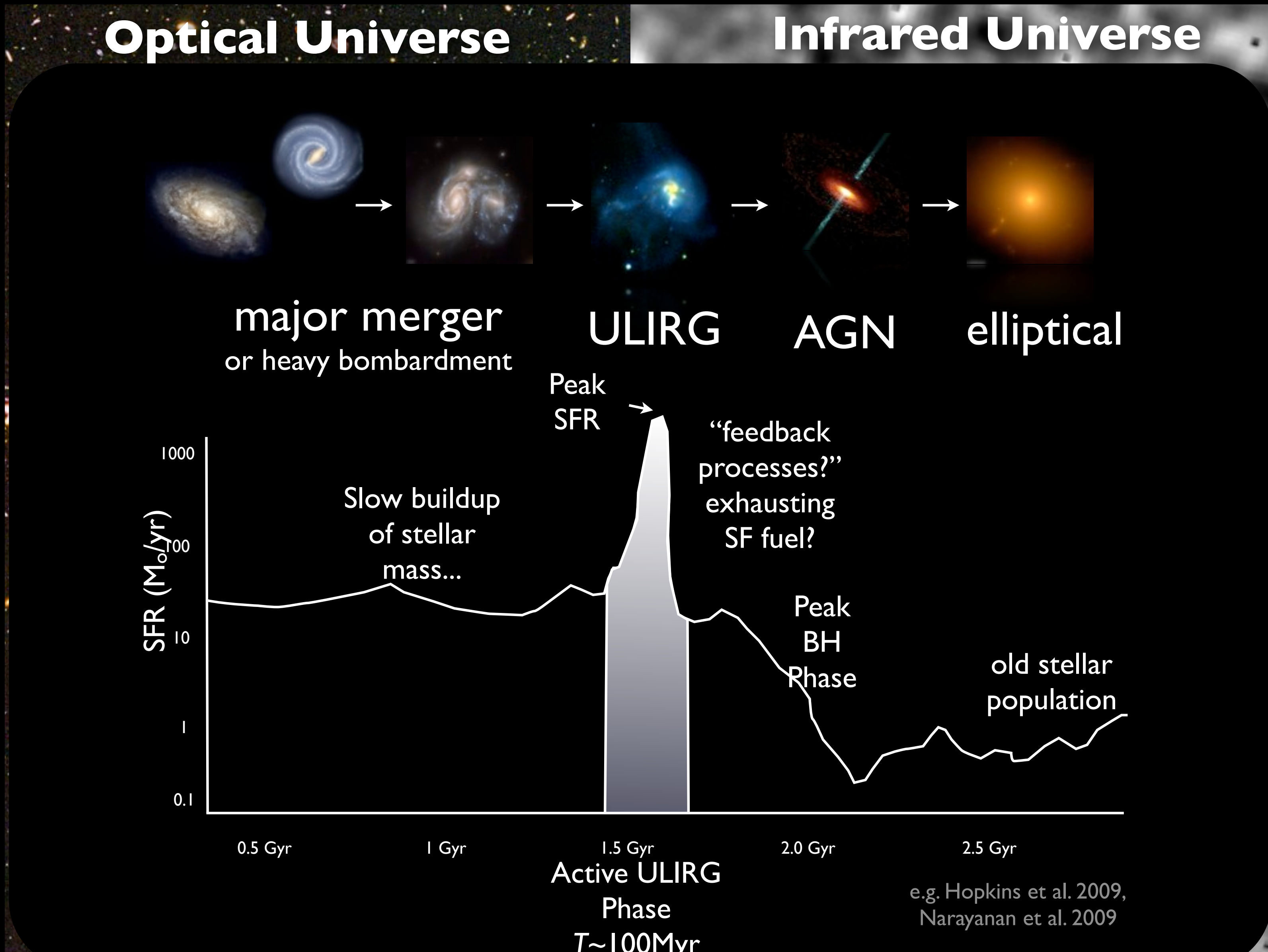
(star-bursting galaxies!)

What kind of galaxies do we detect with Herschel?



What are Dusty Star Forming Galaxies?

Illustration from Caitlin casey

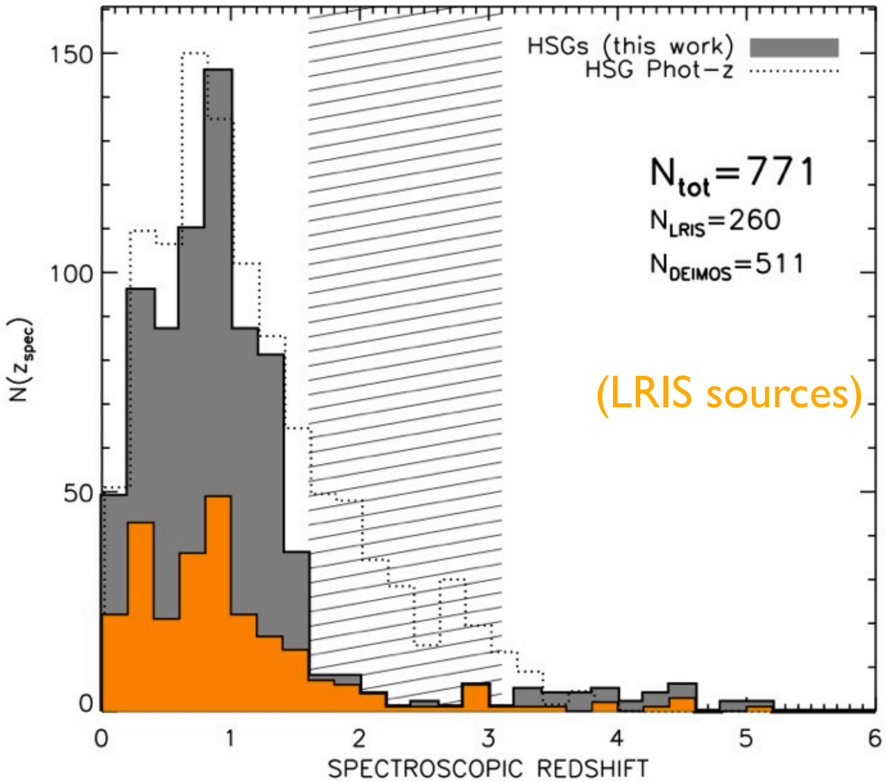


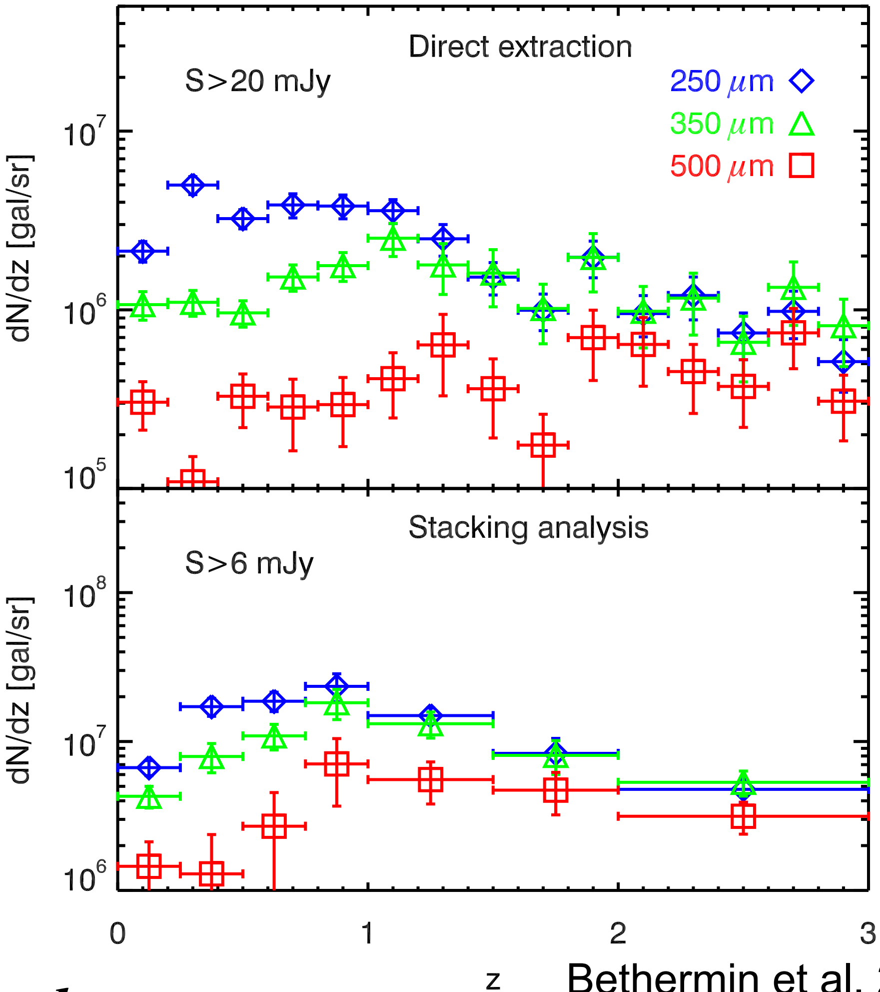
What are Dusty Star Forming Galaxies?

Illustration from Caitlin casey

Redshift distribution of SPIRE Sources?

Caitlin Casey et al. 2012 (UCI postdoc; UT Austin faculty from fall 2015)





Keck LRIS/DEIMOS followup.
z peak is around z~1 (250 micron dominated)

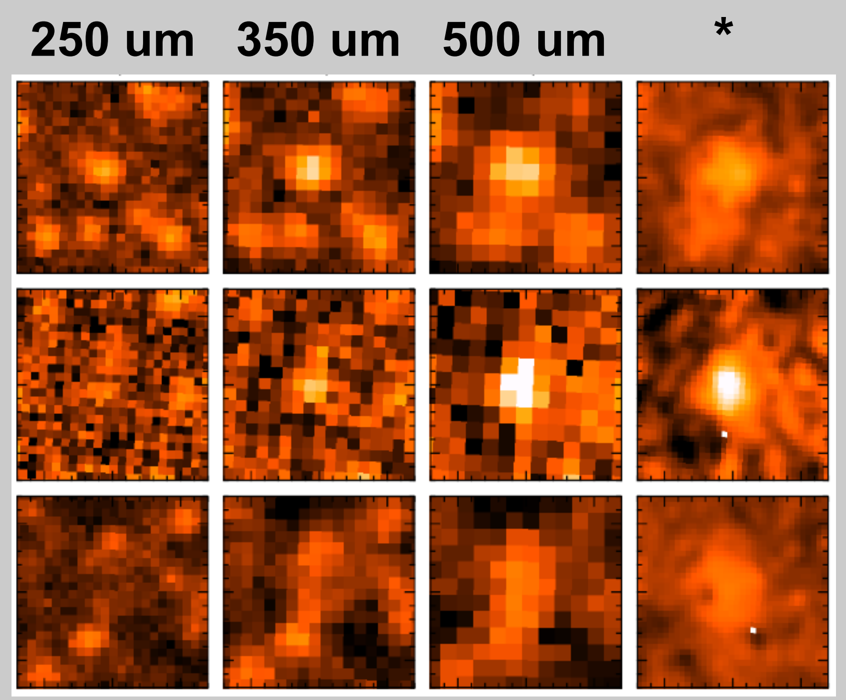
~1000 redshifts in the optical

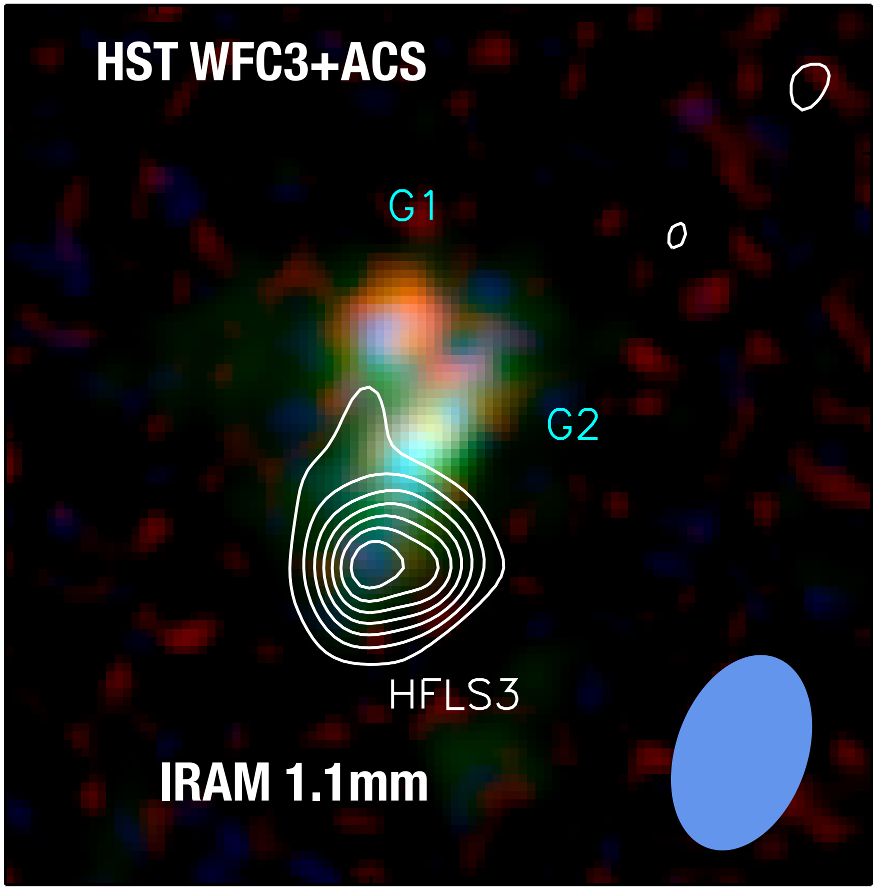
Bethermin et al. 2012

Redshift gap; z > 1.5 highly incomplete.

500 um peaked sources $S_{250} < S_{350} < S_{500}$: z > 4?

*Confusion reduced S(500) – fS(250)

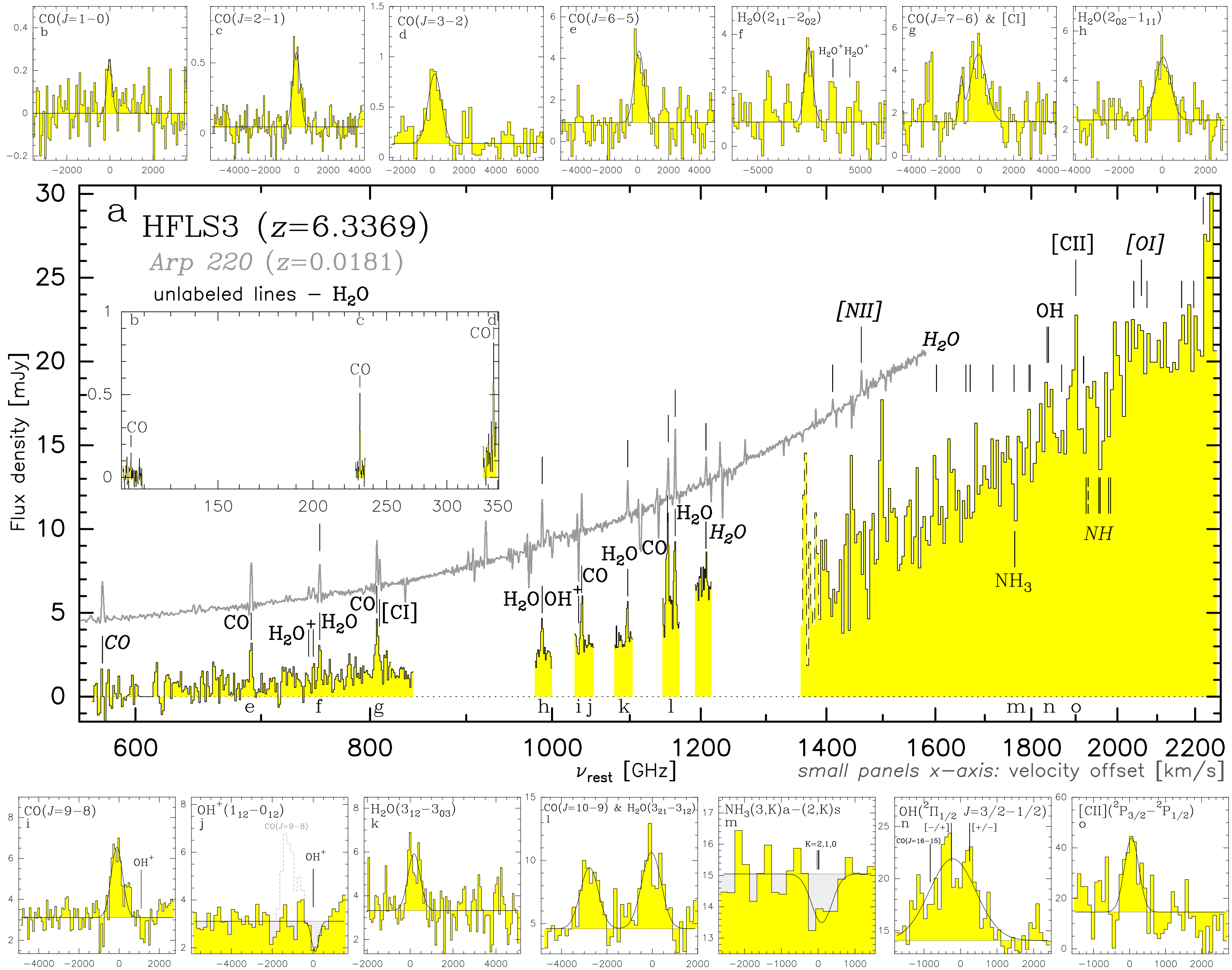


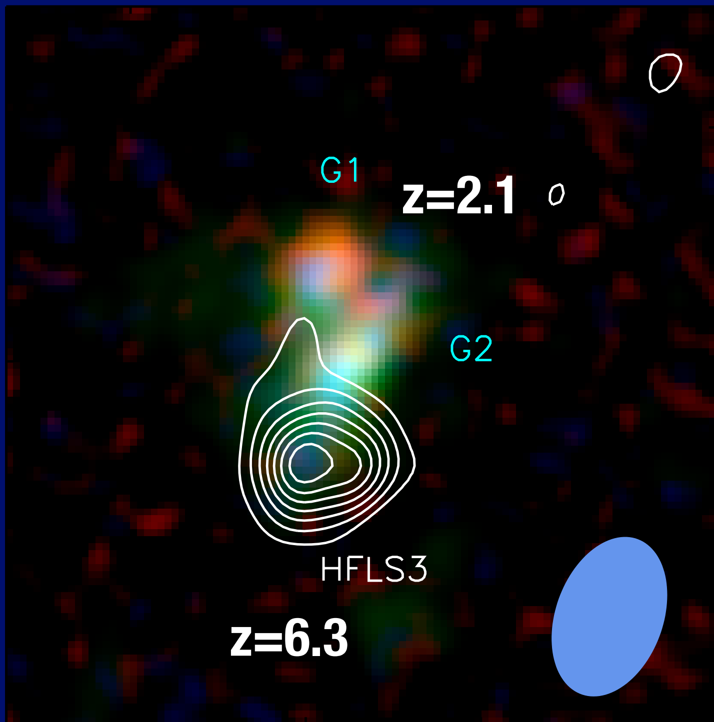


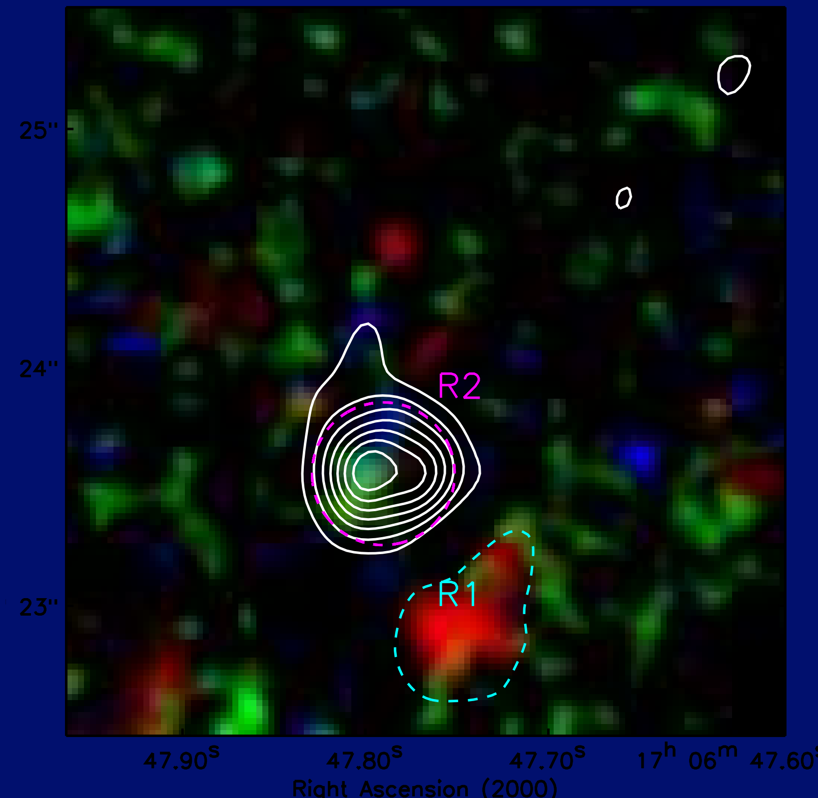
These could be:
$z = 1.5$, $T_{dust} = 20$ K ULIRGs or
$z = 5$, $T_{dust} = 35$ K HLIRGs…

z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D. et al. Nature 2013; Cooray et al. 2014


HFLS3 (z=6.3369)
Arp 220 (z=0.0181)
unlabeled lines – H2O
Flux density [mJy]
ν rest [GHz]
small panels x–axis: velocity offset [km/s]
[CII]
[OI]
[NII]
OH
NH3
NH
CO
[CI]
OH+





Weakly lensed by two z=2.1 galaxies with magnification 1.6 +/- 0.3

L_{FIR} = 6X10^{12} $L_\odot$

SFR ~ 1300 $M_\odot$/yr

T_{DUST} = 55 ± 10 K

M_{DUST} > 10^9 $M_\odot$

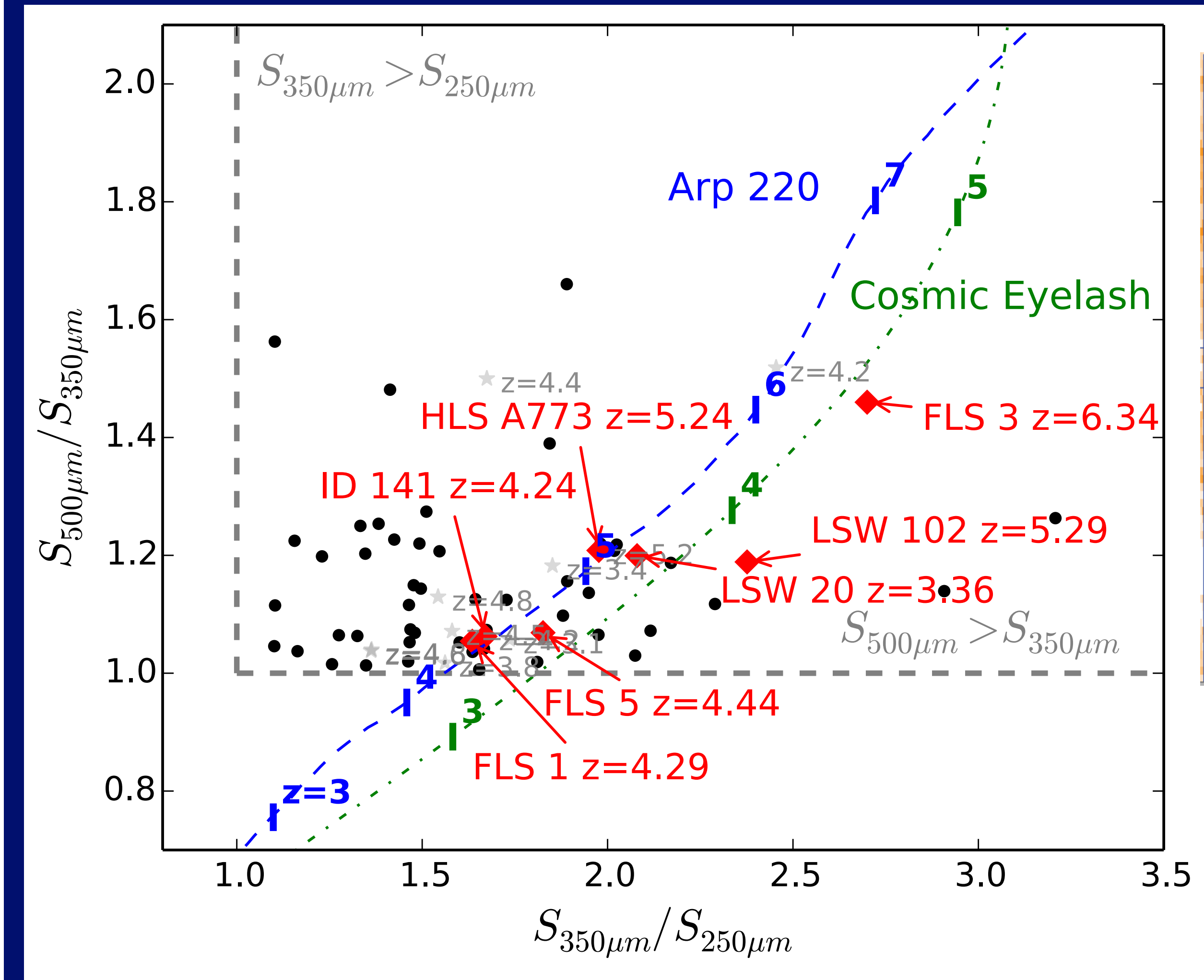
M_{STARS} ~ 5X10^{10} $M_\odot$

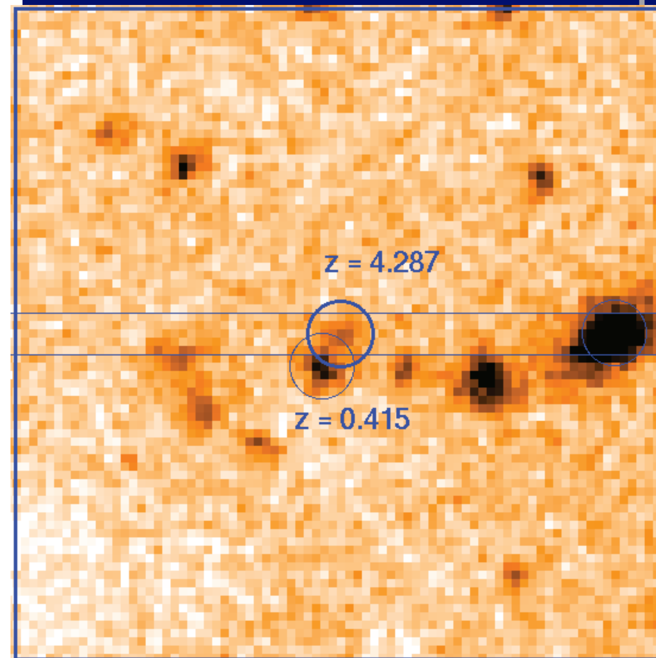
M_{GAS} ~ 10^{11} $M_\odot$

No evidence for a quasar/massive AGN!

z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D. et al. Nature 2013; Cooray et al. 2014



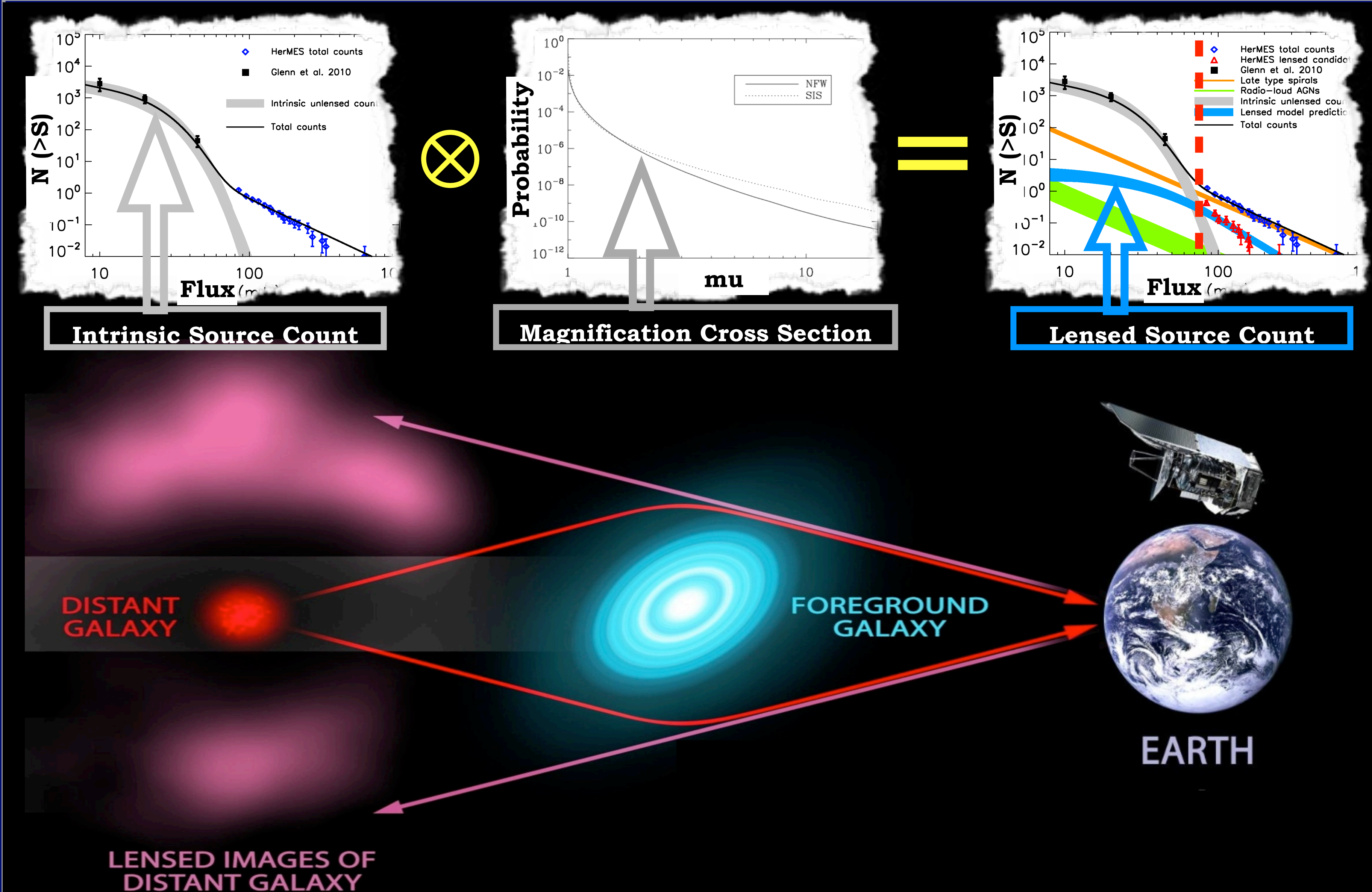


Are all Herschel-detected z >4 galaxies weakly lensed?

SPT (Vieira et al. 2013) finds z > 3 bright strongly lensed (mag> 5) galaxies at 1.4mm

Other “red” galaxies in Herschel

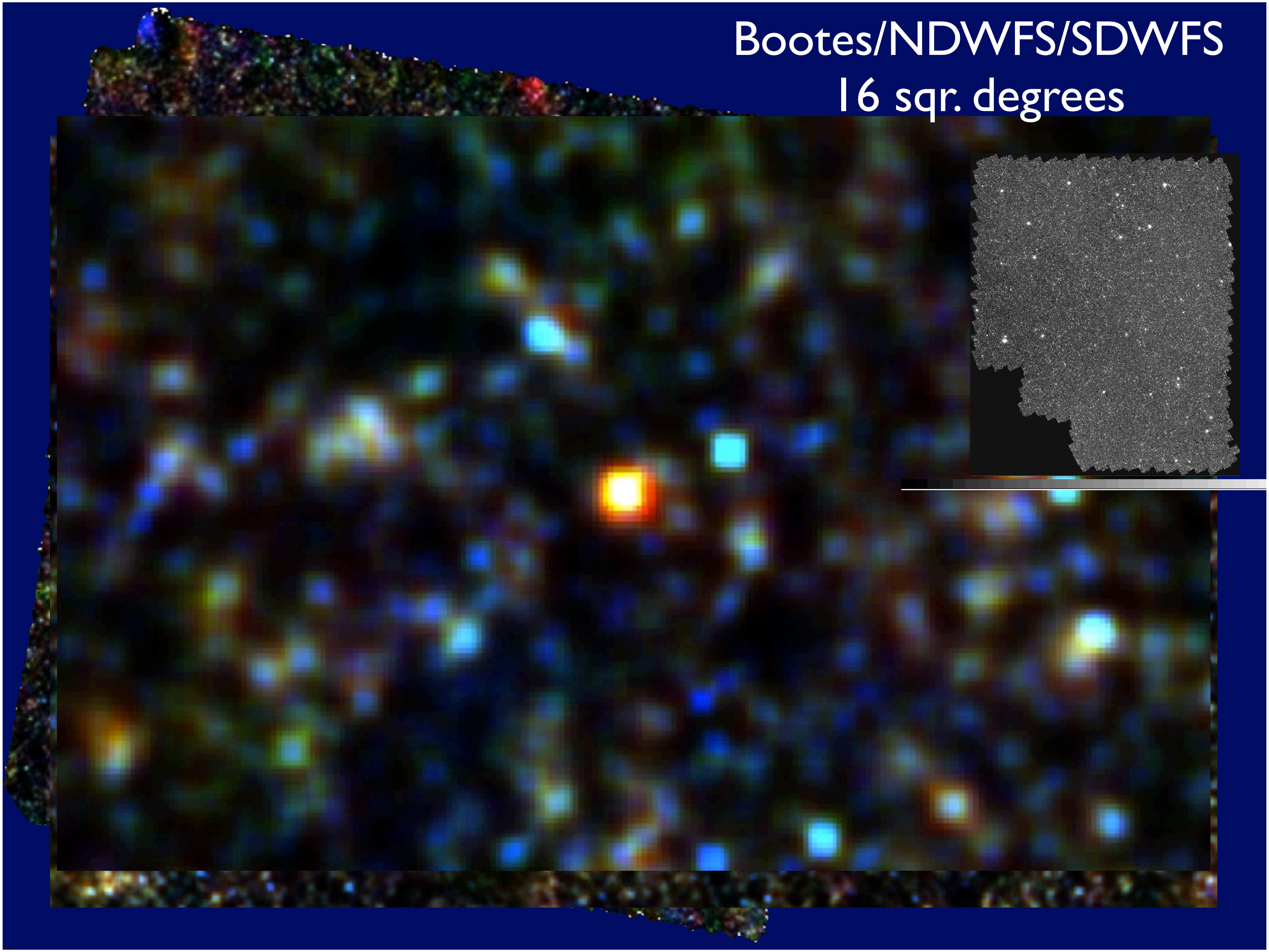
Dowell et al. 2013 ApJ

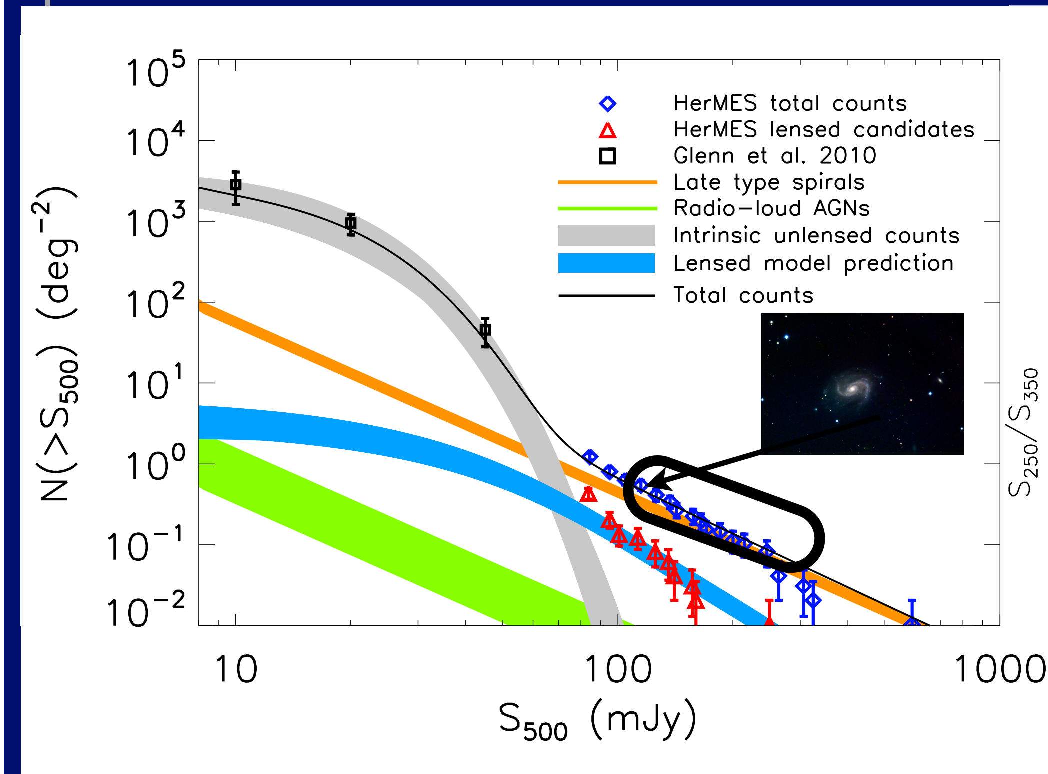


Efficient Selection of Strongly Lensed SMGs

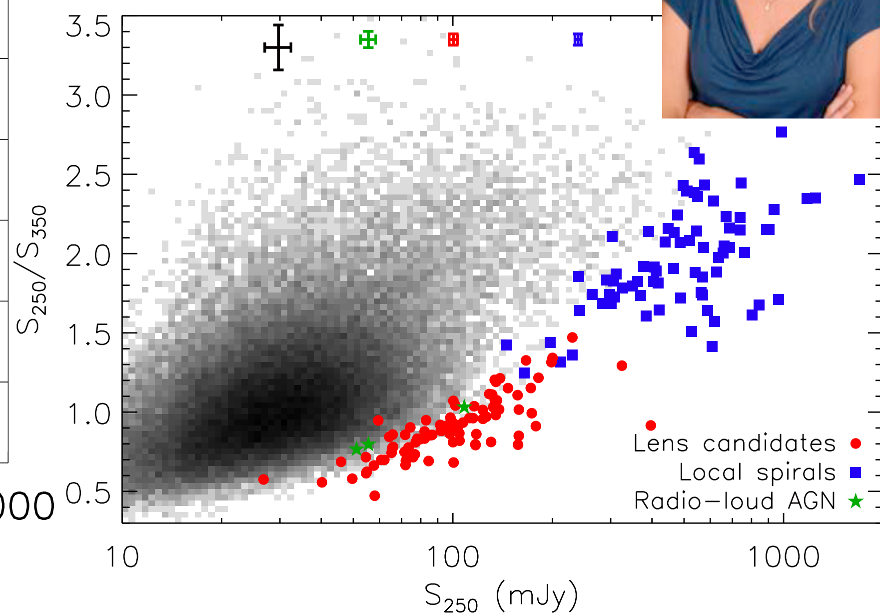
Blain (1996), Negrello et al. (2007), Wardlow et al. (2012)

Bootes/NDWFS/SDWFS
16 sqr. degrees





Julie Wardlow et al. 2012, ApJ
(former UCI postdoc; now at DARK)

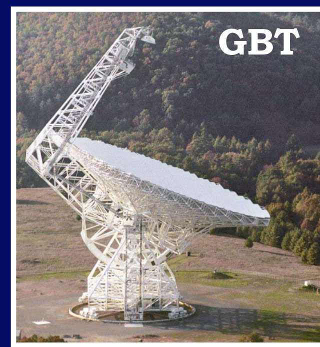


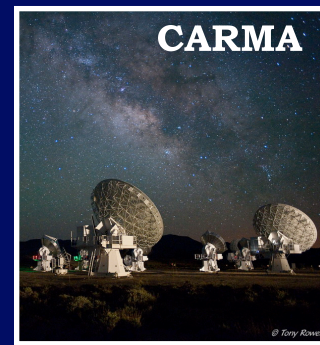
- Lensing: Flux boosted (magnified)
- Can study fainter objects than usually available.
- Can study spatial distribution of gas, dust, stars at higher resolution than with normal galaxies at the same distances.

The Nature of Brightest high-z Herschel Galaxies

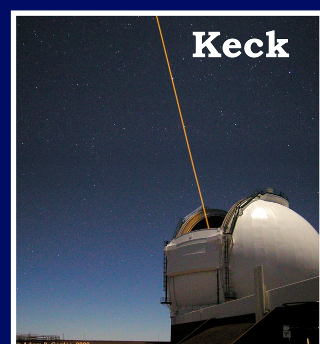
Negrello et al. 2010 Science; Wardlow et al. 2012, ApJ; Bussman et al. 2012 ApJ

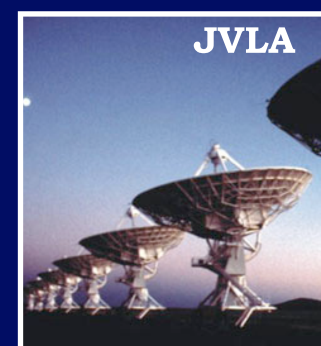
Source CO Redshift





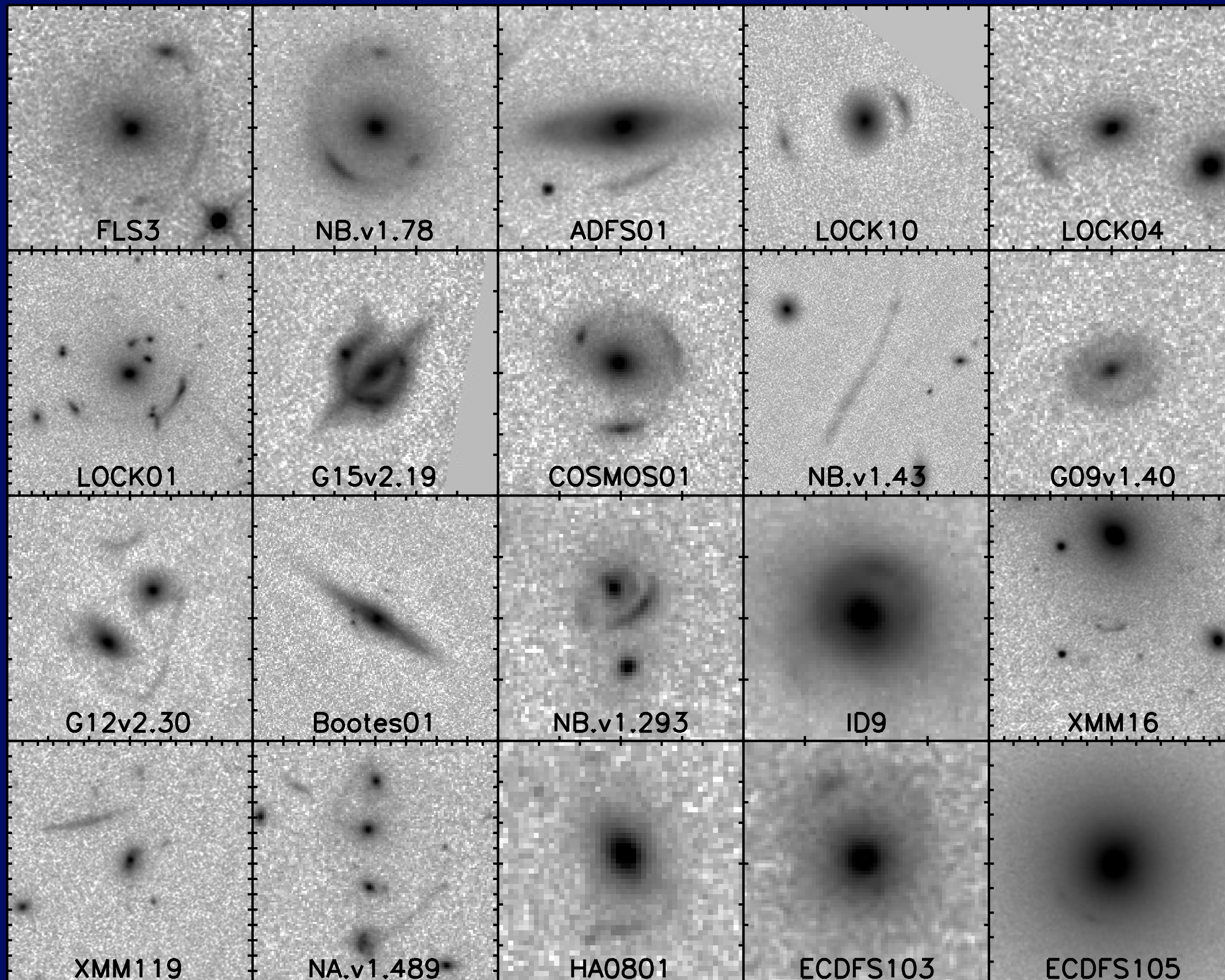
High-Resolution Imaging





Extensive Ground-based Follow-up Observations

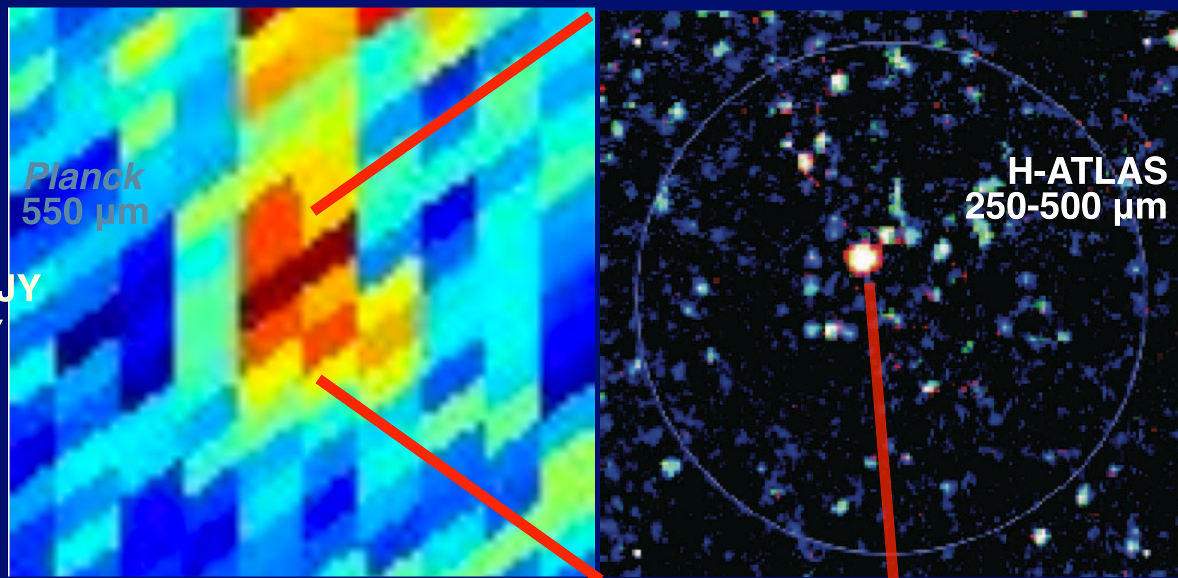
Jae Calanog
UCI PhD 2014
Faculty Mesa
College, San Diego



Keck LGS-AO Imaging (~15+ nights) + HST SNAPs

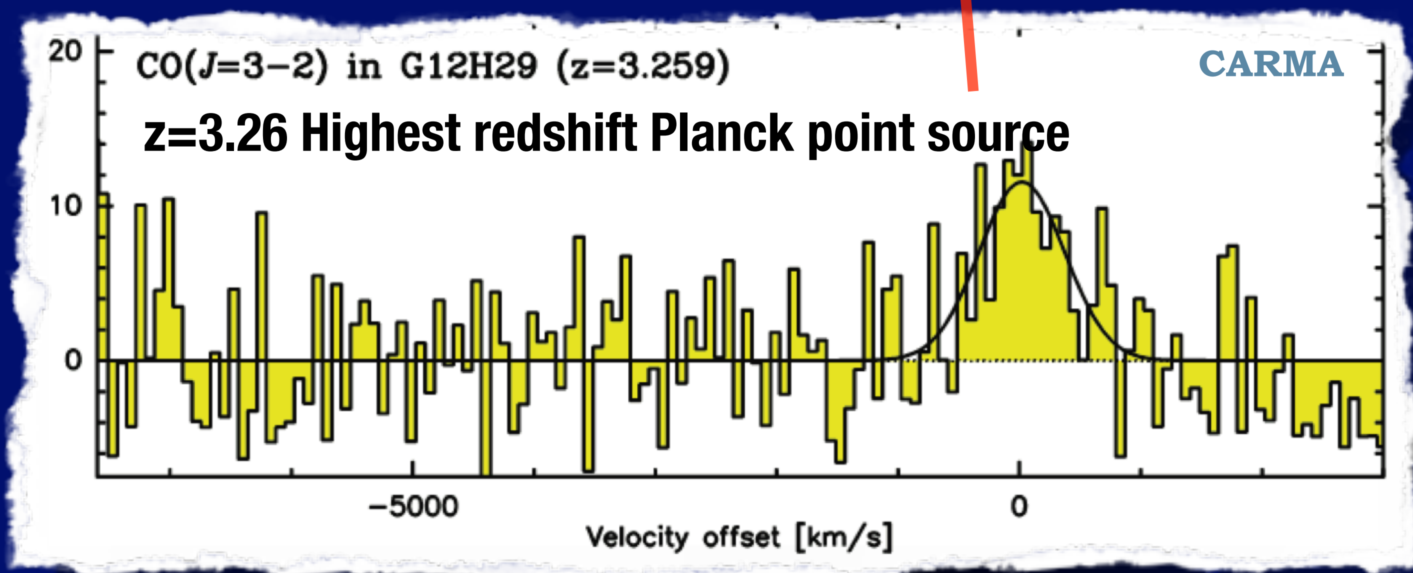
Calanong et al. 2014

S_{550} = 1.07 ± 0.12 JY
S_{350} = 1.1 ± 0.2 JY



(brightest source)
S_{250} = 320 ± 20 mJy
S_{350} = 380 ± 60 mJy
S_{500} = 300 ± 20 mJy

Z_{CO} = 3.26



A lensed Planck source resolved by Herschel (in ATLAS)

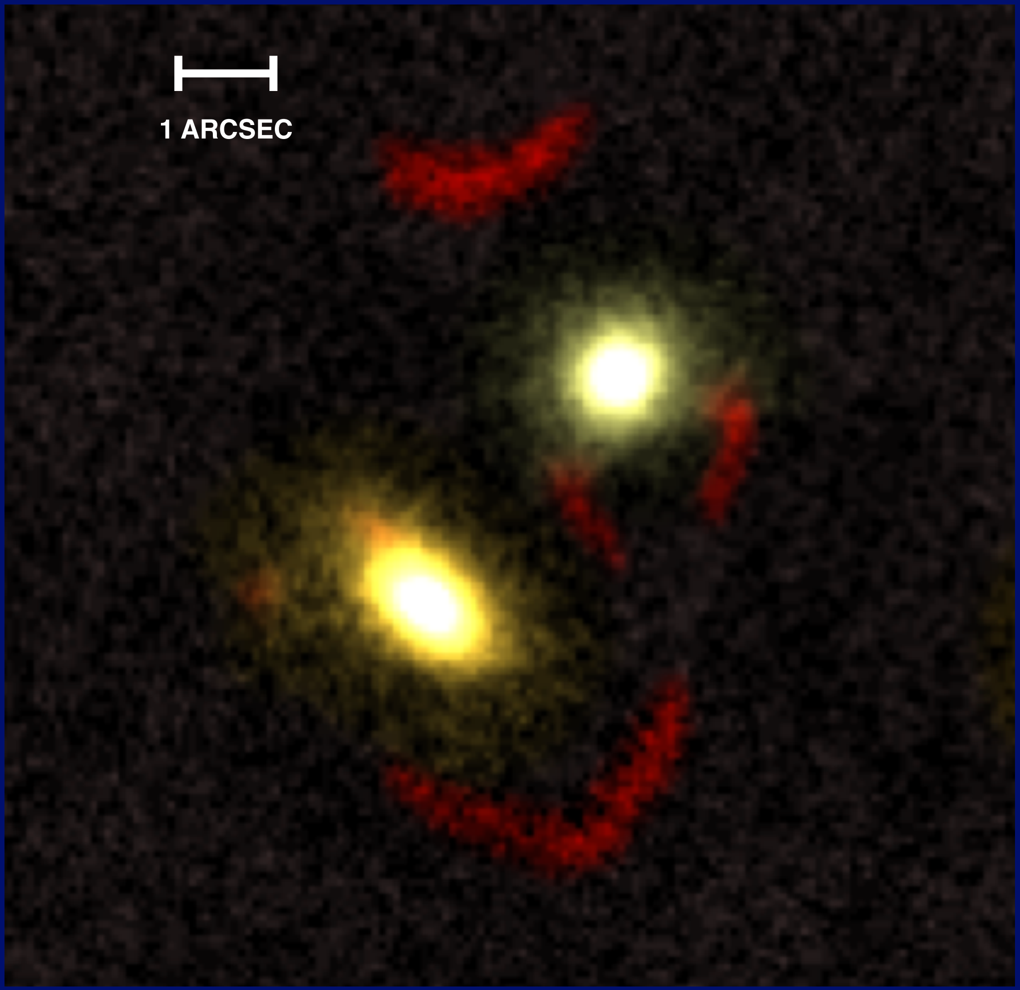
Fu, Hai et al. 2012, ApJ

$L_{FIR} = 1.6 \times 10^{13} L_{\odot}$
SFR ~ 1900 $M_{\odot}$/yr
$T_{DUST} = 62 \pm 3$ K

No evidence for AGN

$M_{DUST} = 6 \times 10^{8} M_{\odot}$
$M_{STARS} = 3 \times 10^{10} M_{\odot}$
$M_{GAS} = 7 \times 10^{10} M_{\odot}$
$M_{DYNAMICAL} = 3 \times 10^{11} M_{\odot}$

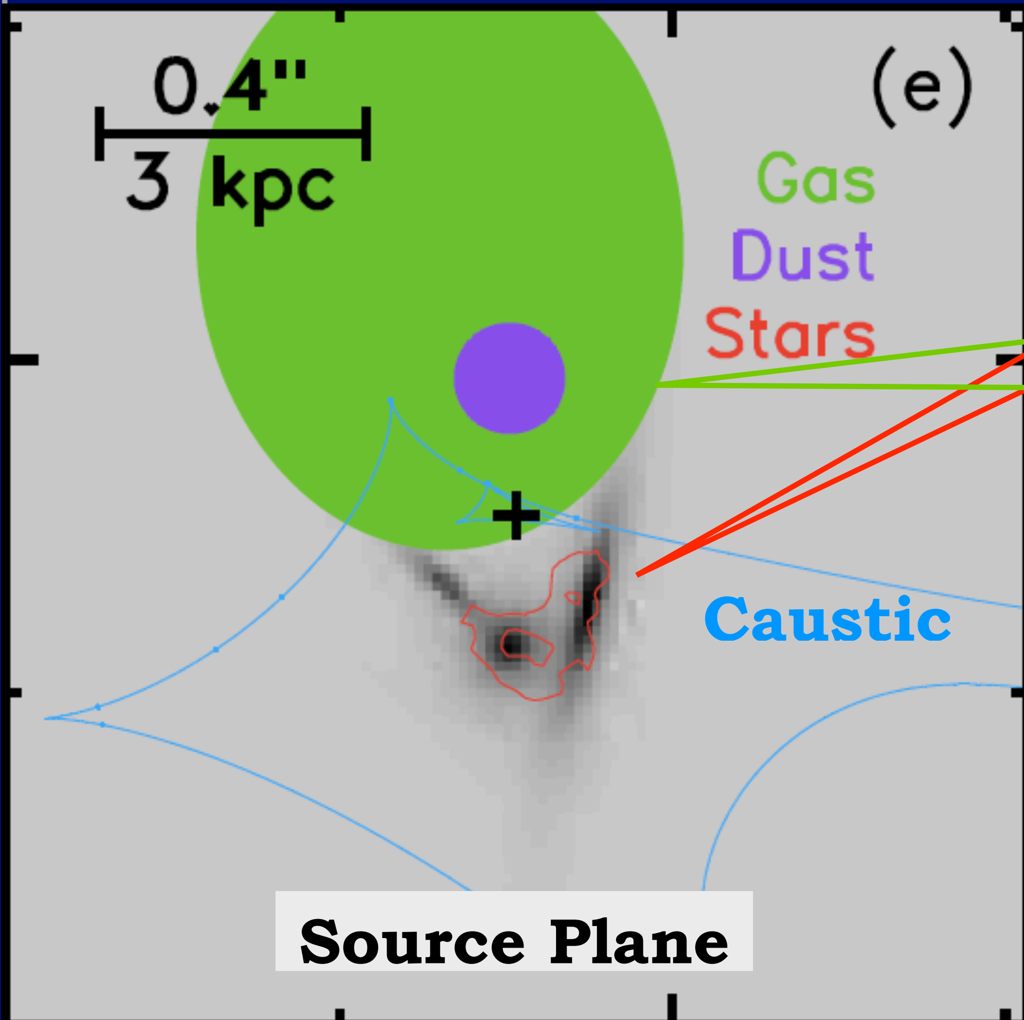
Gas-rich (70% of baryons in gas)
Young (M_{STARS}/SFR~20 Myr)
Short Star-burst (M_{GAS}/SFR~40 Myr)

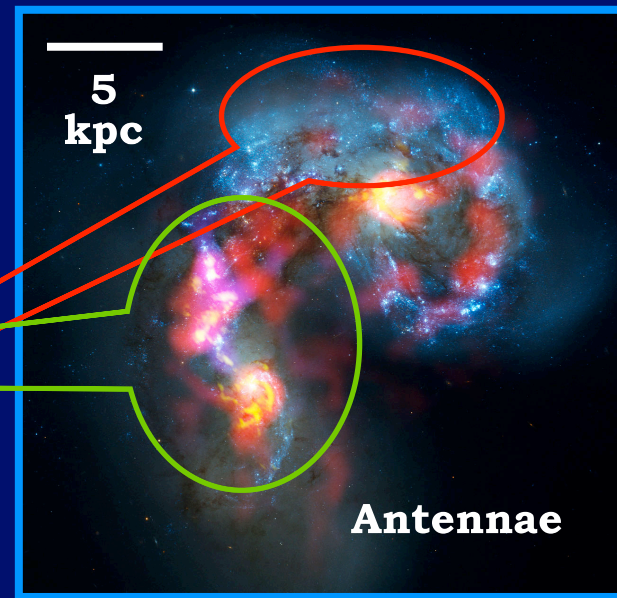


Hai Fu et al. 2012, ApJ (former UCI postdoc; U. of Iowa faculty)

Differential Magnification:

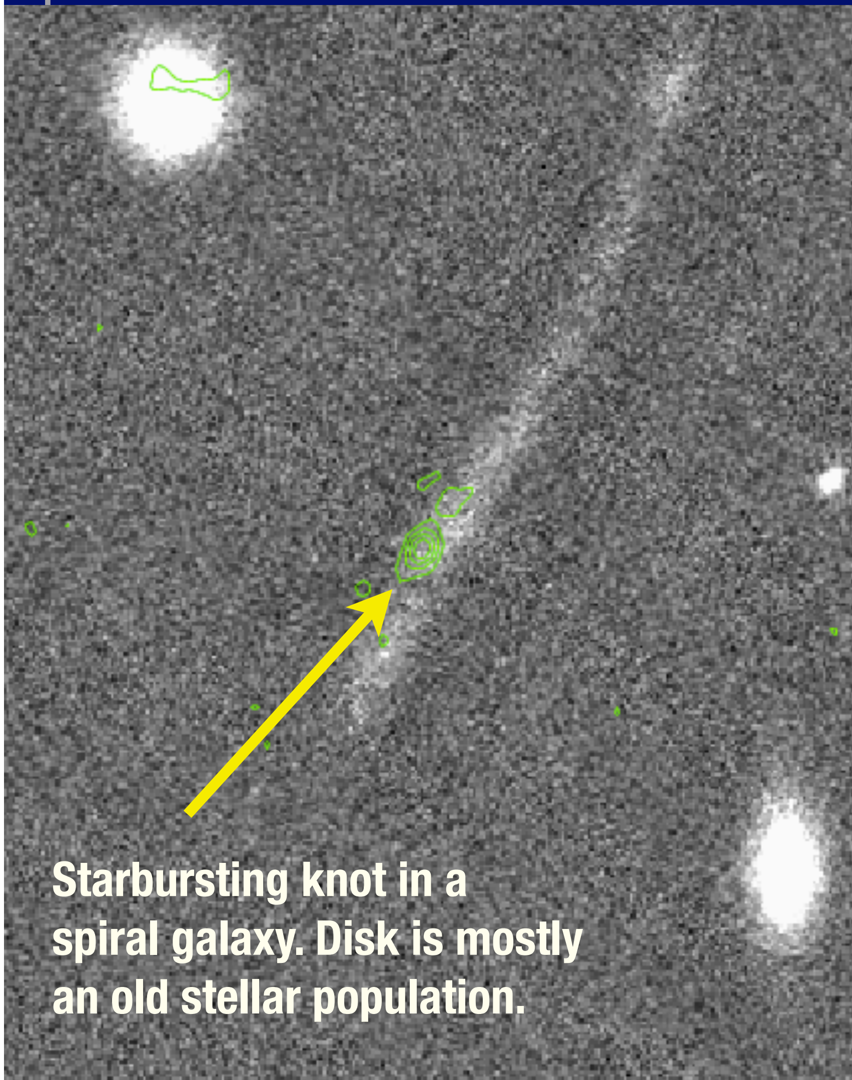
μ(Stars) ≈ 17, μ(Dust) ≈ 8, μ(Gas) ≈ 7

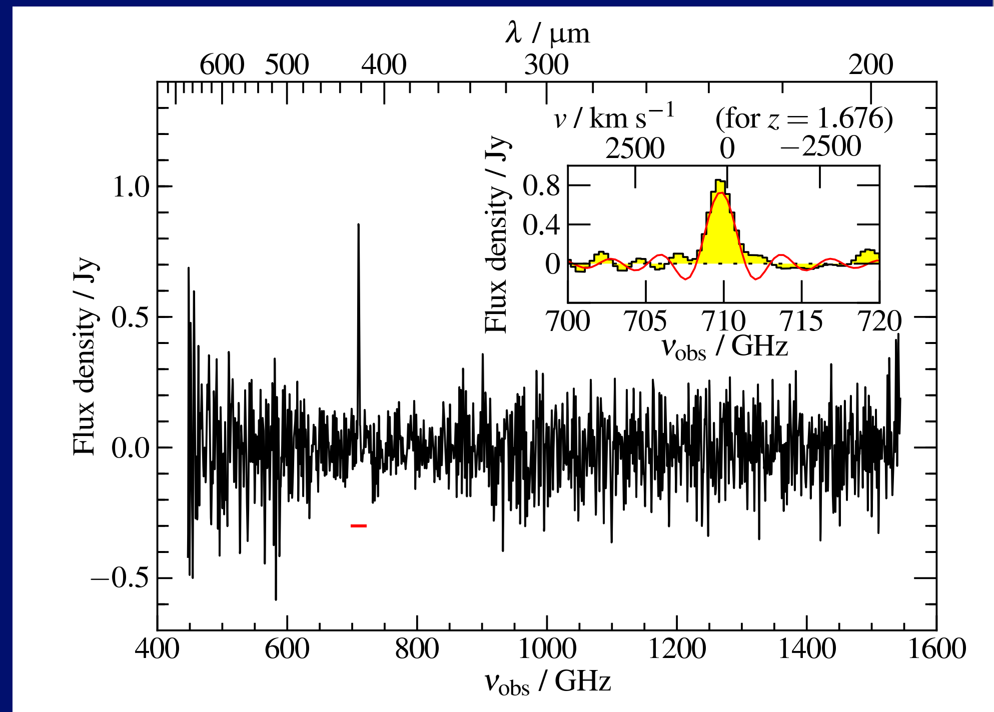




Source Plane Morphologies

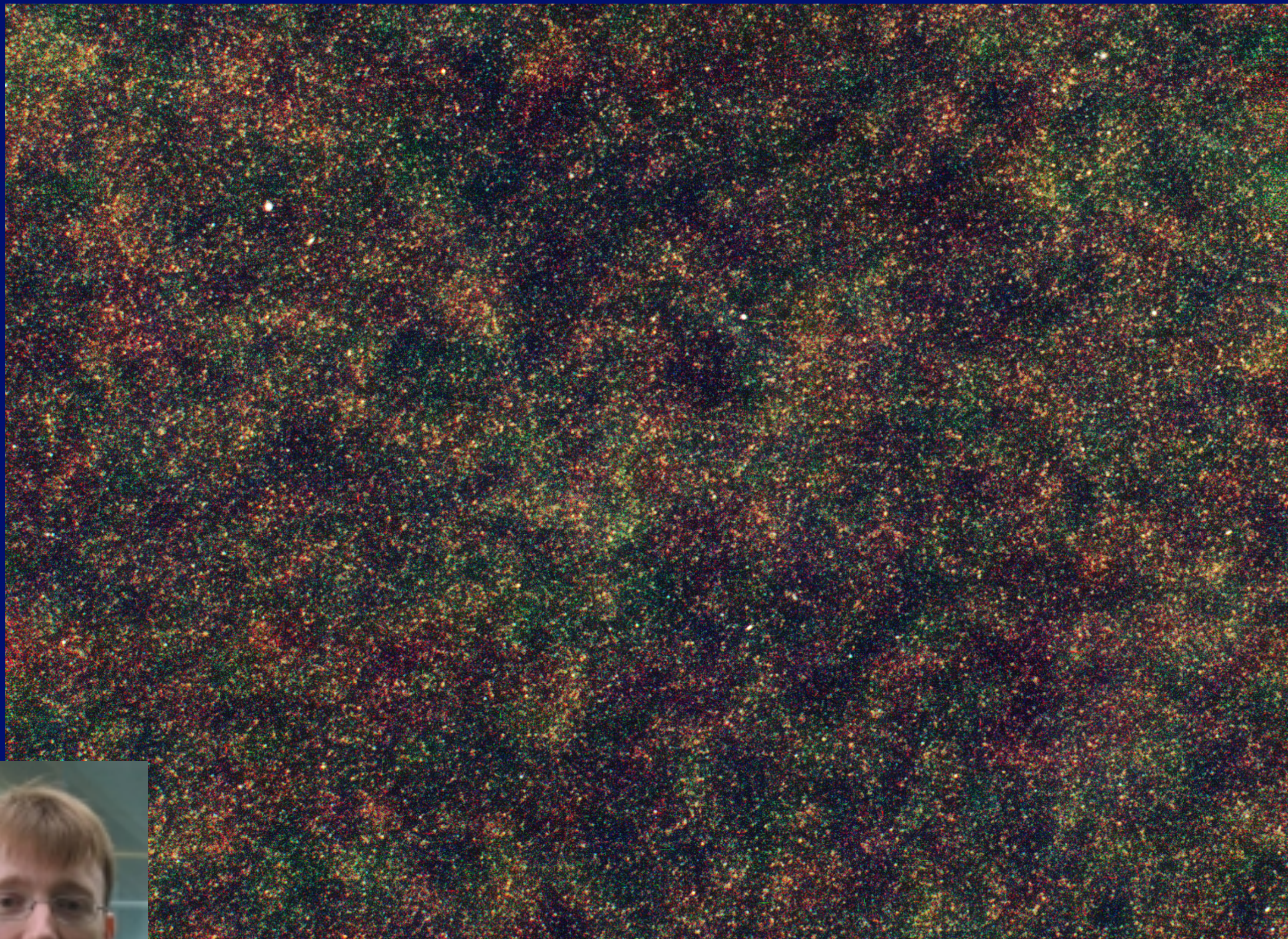
H-ATLAS: 650 sq. degrees. ~2 lensed Planck ERCSC sources. One in HerMES over 370 sq. degrees.





z=1.68, determined from the Herschel-SPIRE/FTS spectrum detecting the 158 micron CII line
George et al. 2014

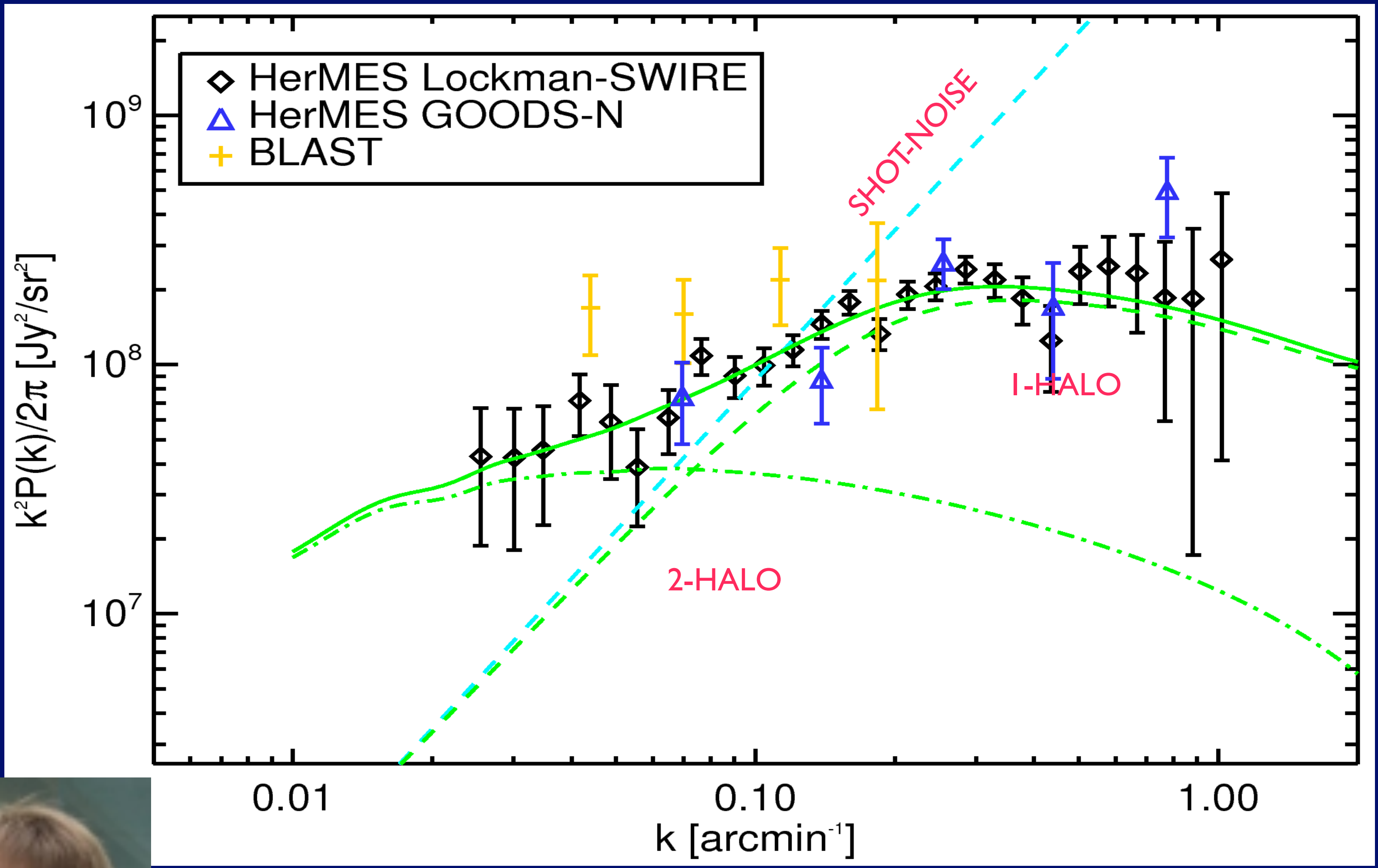
Second Herschel Lensed Source in Planck



Cosmic Infrared Background Fluctuations with SPIRE

Amblard et al. 2011, Nature; Thacker et al. 2013

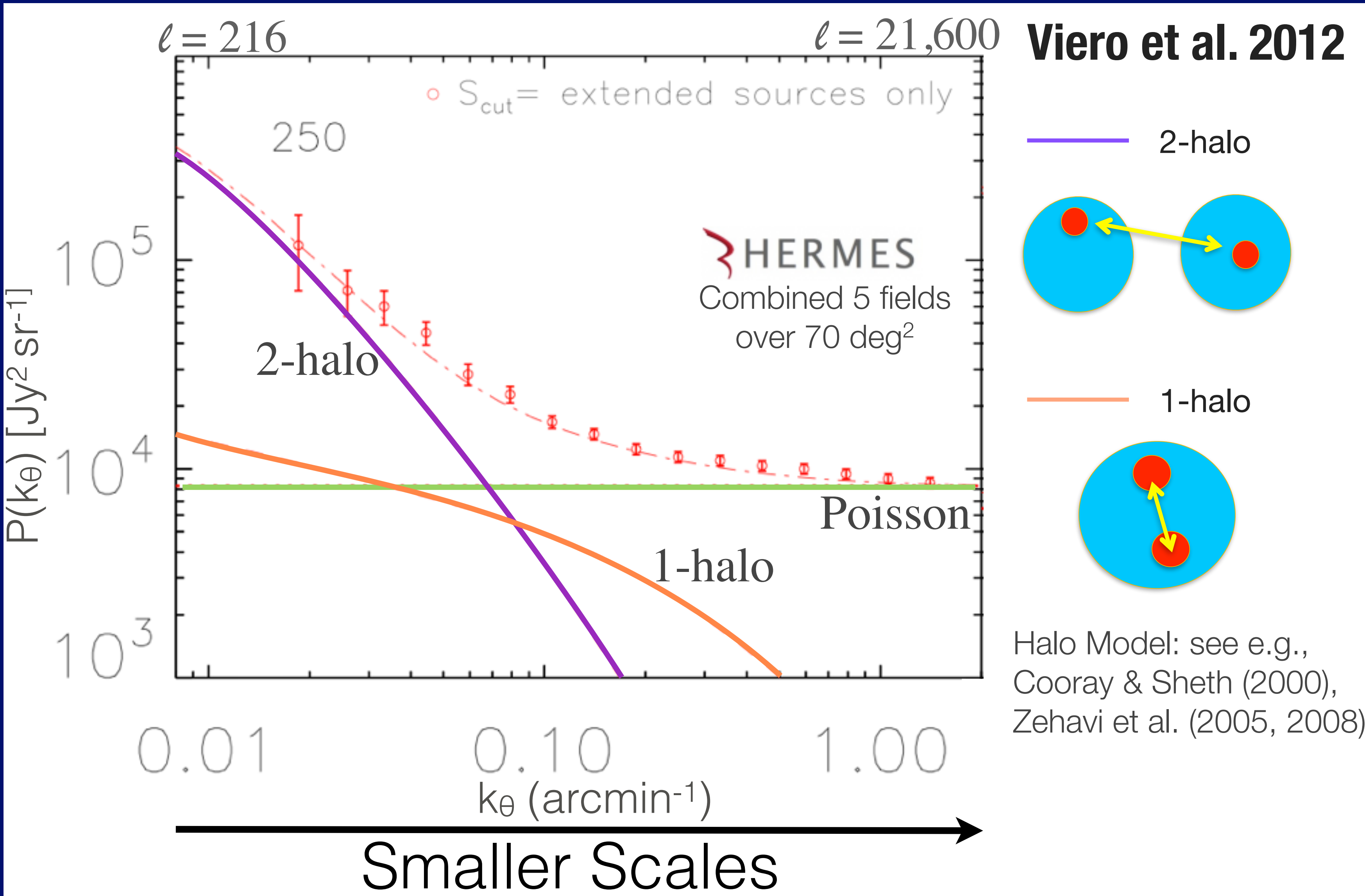
A power-law template is not a good approximation for CIB power spectrum (c.f. Addison et al. 12)



Alex Amblard (former UCI postdoc; NASA Ames Staff)

Cosmic Infrared Background Fluctuations with SPIRE

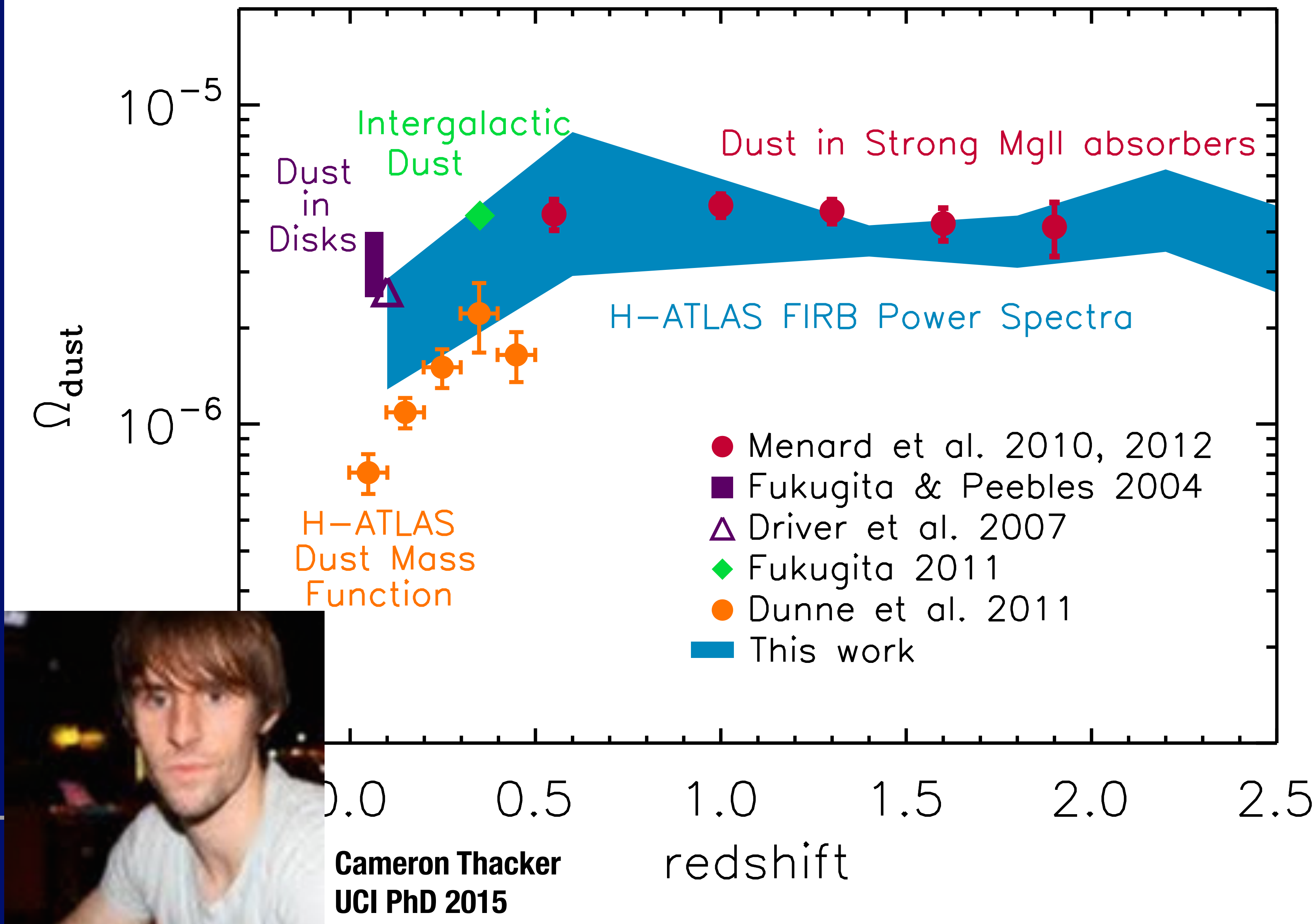
Amblard et al. 2011, Nature; Thacker et al. 2013



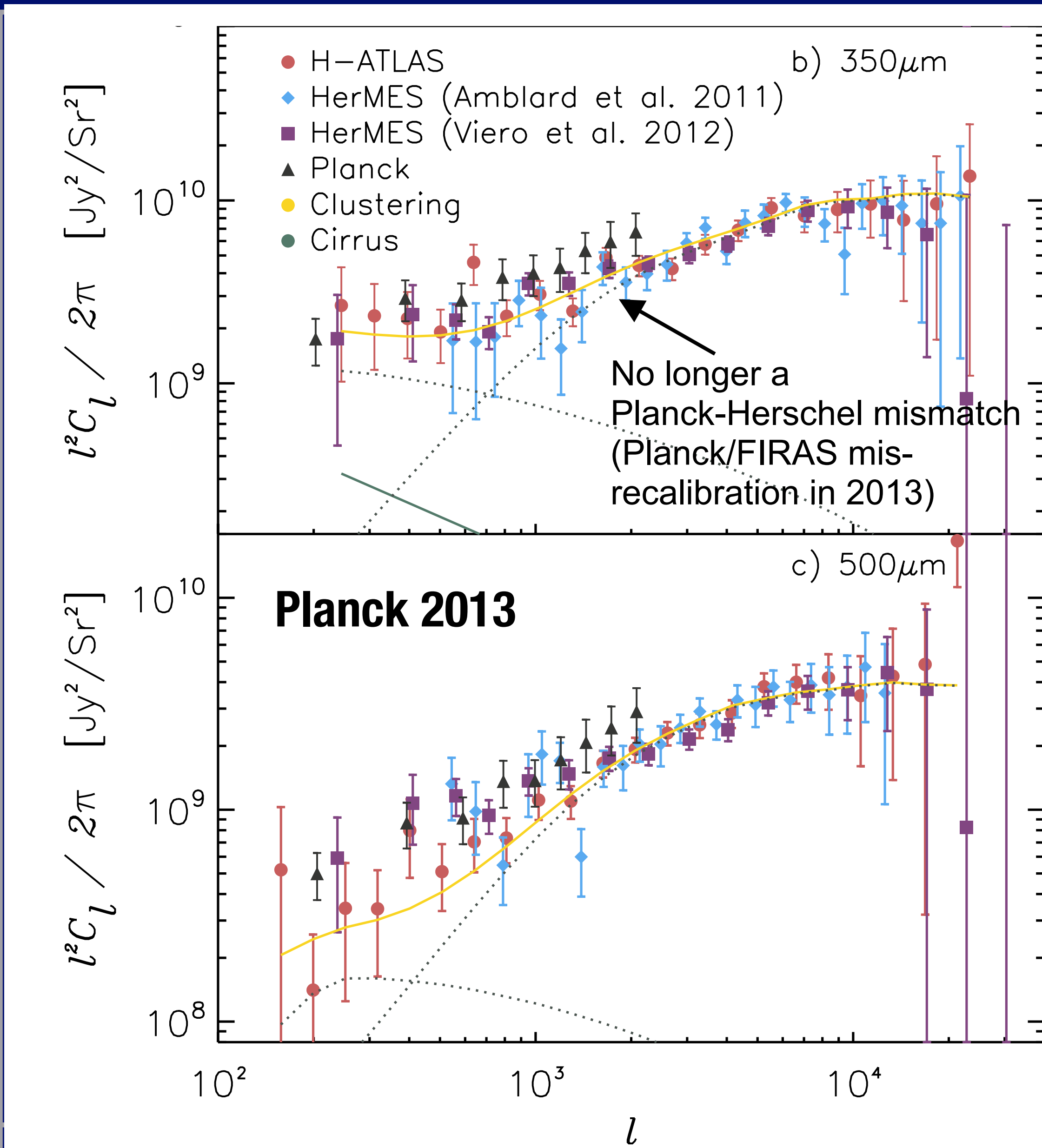
Cosmic Infrared Background Fluctuations with SPIRE

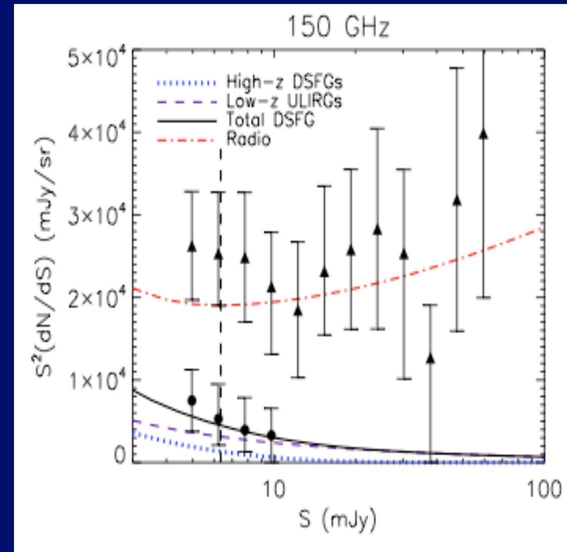
Amblard et al. 2011, Nature; Thacker et al. 2013

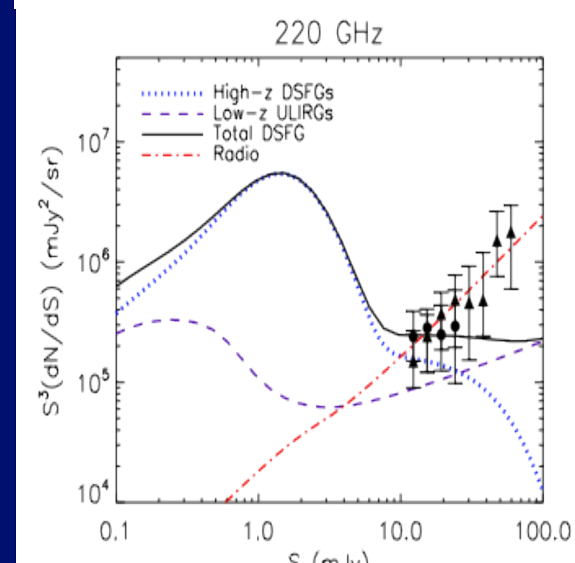
Cosmic Infrared Background Fluctuations = Dust Content



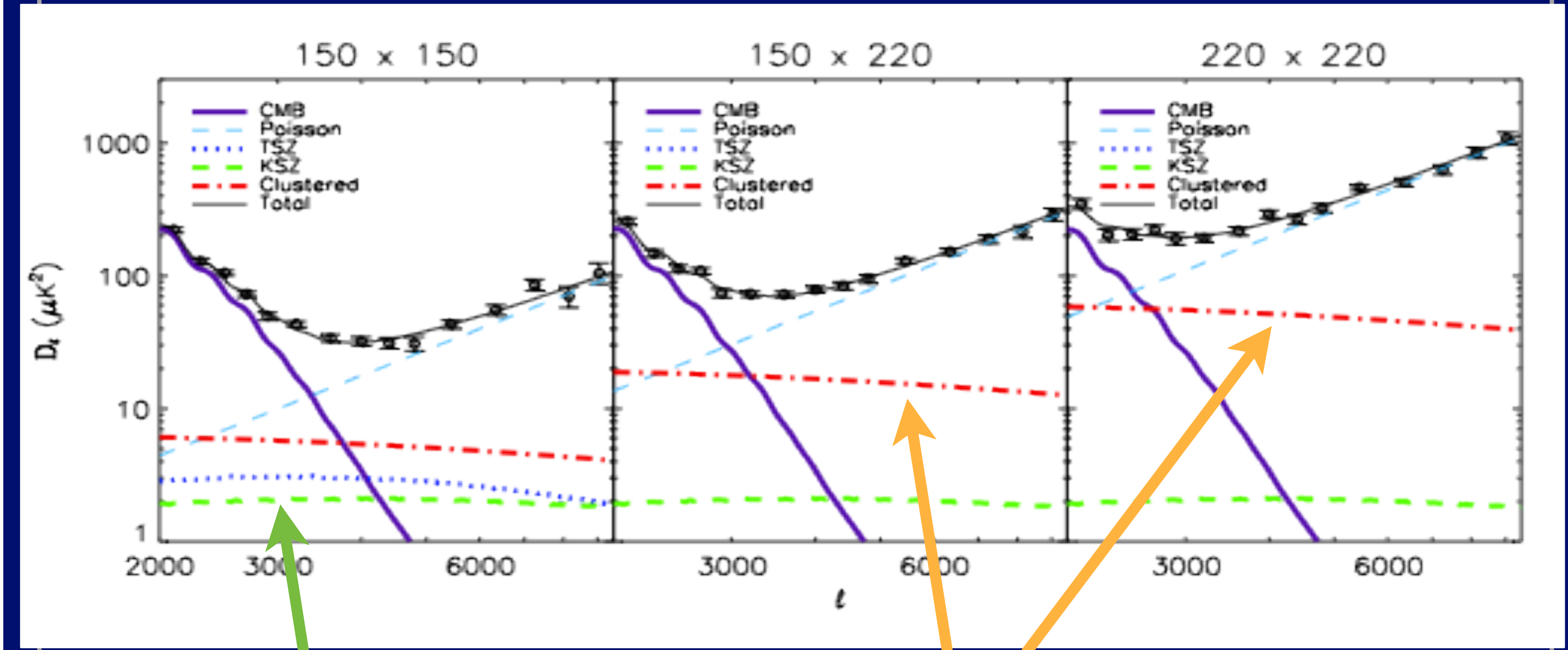
Cameron Thacker
UCI PhD 2015







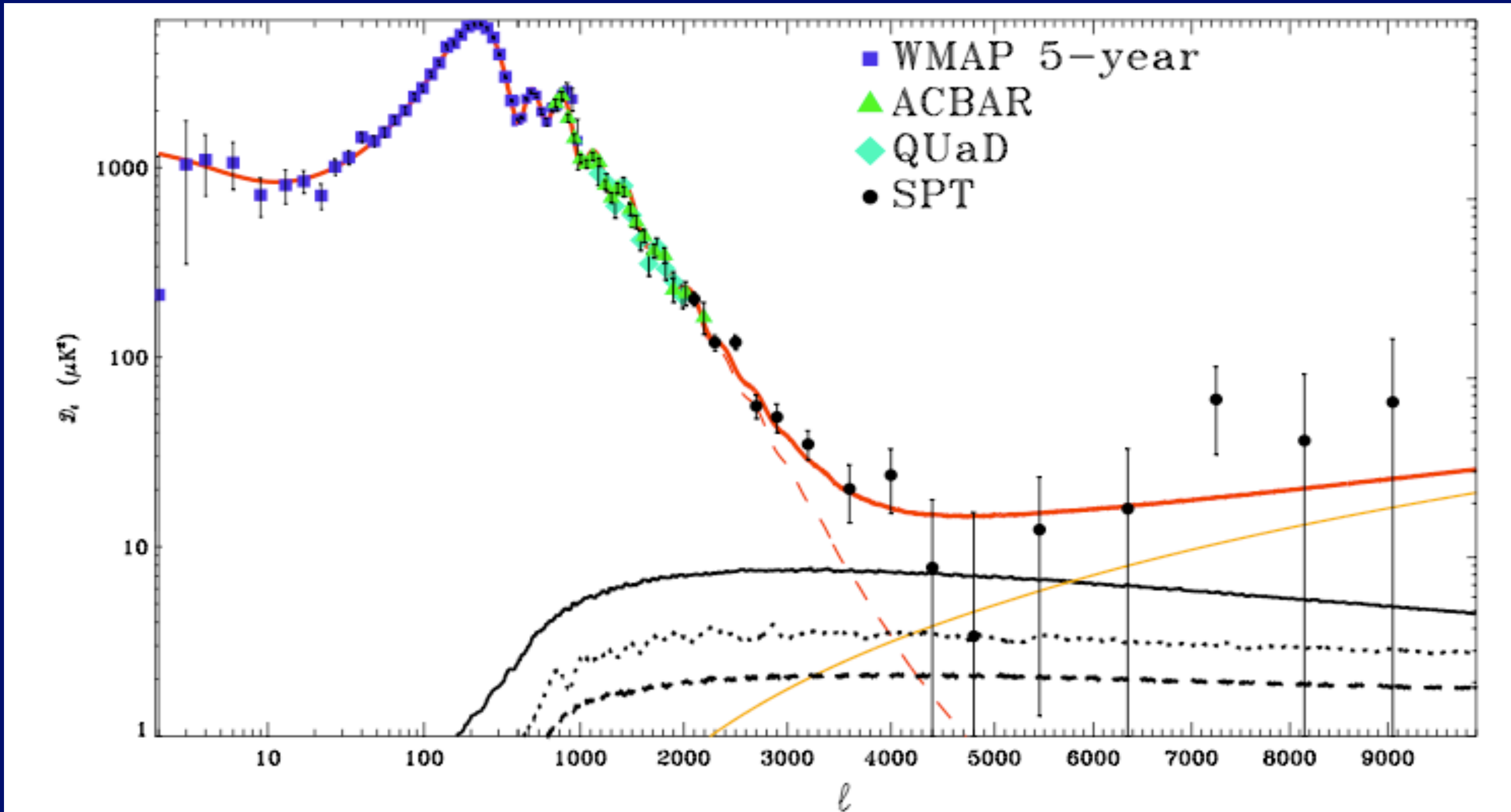
Relation to CMB Experiments



Best-fit sub-mm galaxy-clustering term

Secondary CMB anisotropies: sub-dominant relative to unresolved galaxies

Relation to CMB Experiments



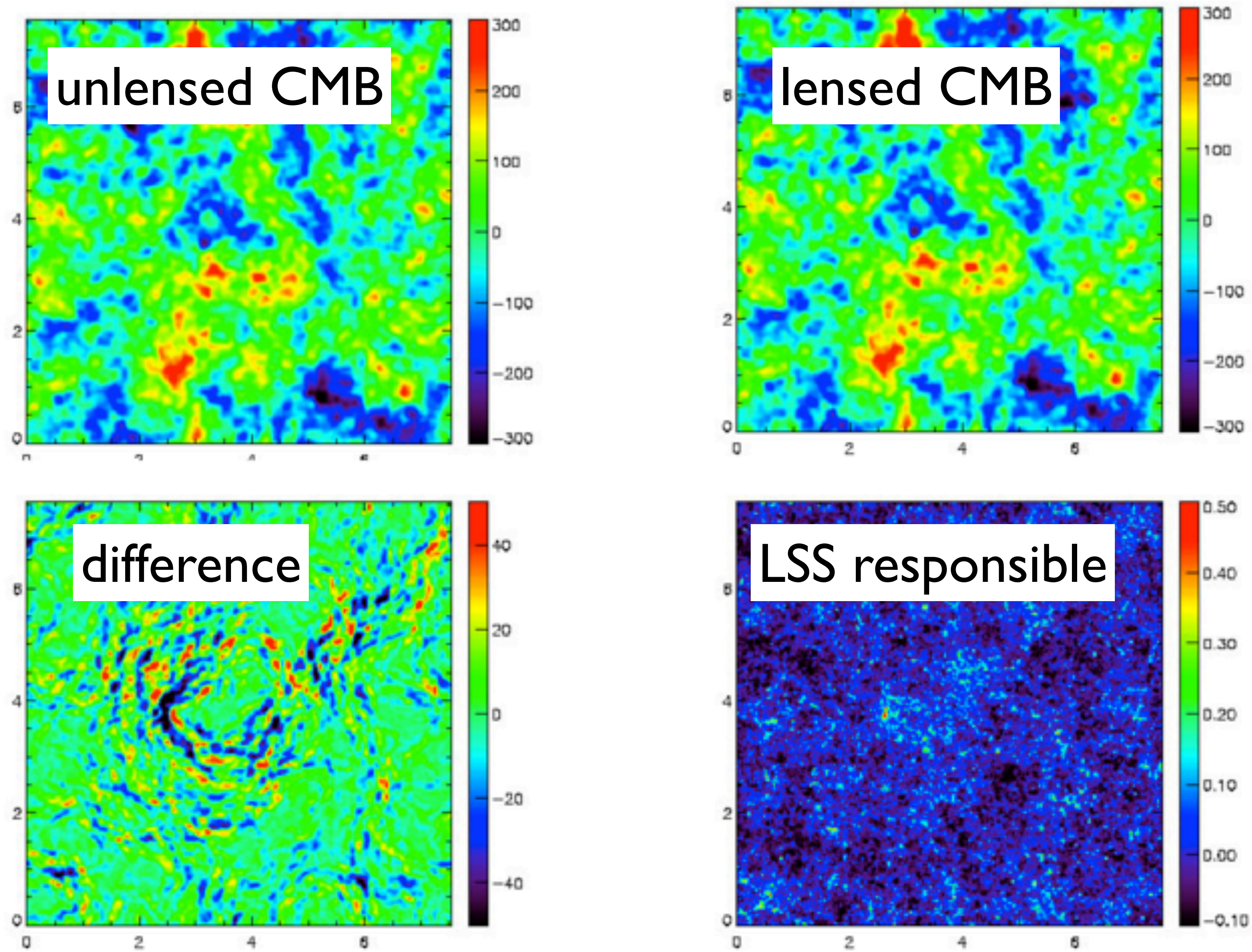
Unresolved sub-mm galaxy fluctuations dominate arcminute scale CMB at > 200 GHz

Challenge to cleanly detect kSZ, Reionization signals (OV, inhomogemous reionize).

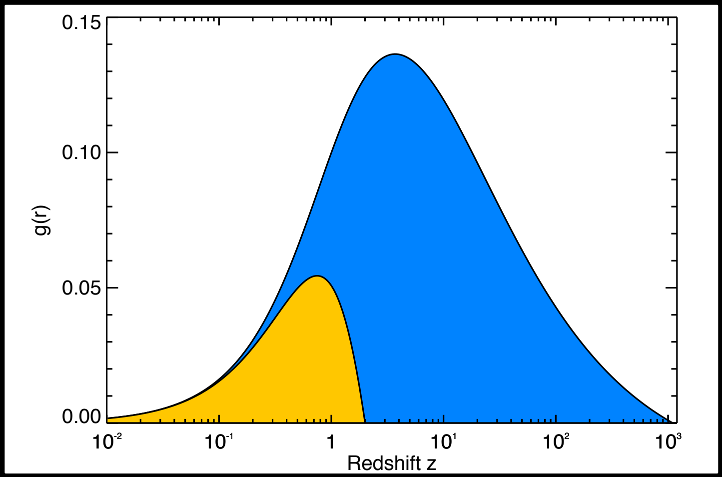
Multi-freq even at small scales if secondary signals are an important science goal.

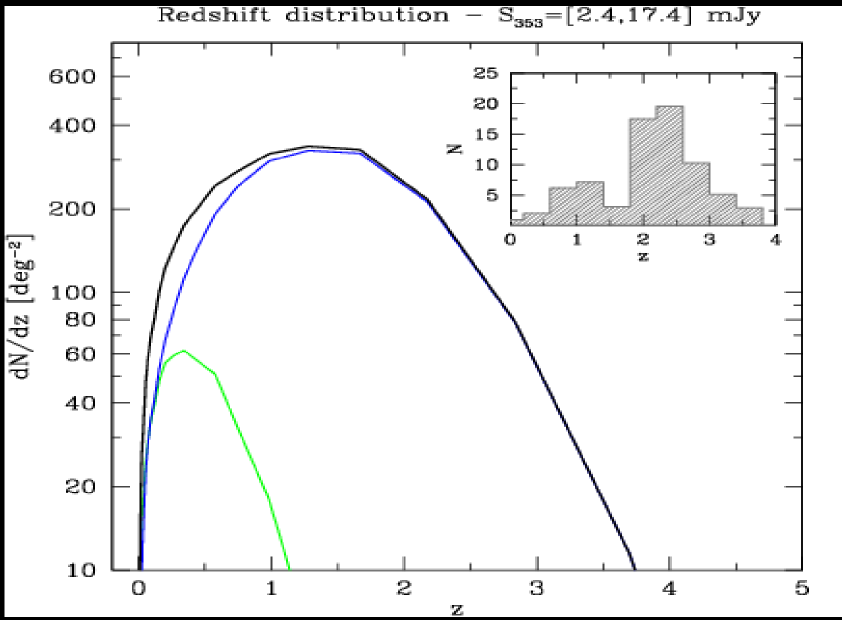
Relation to CMB Experiments

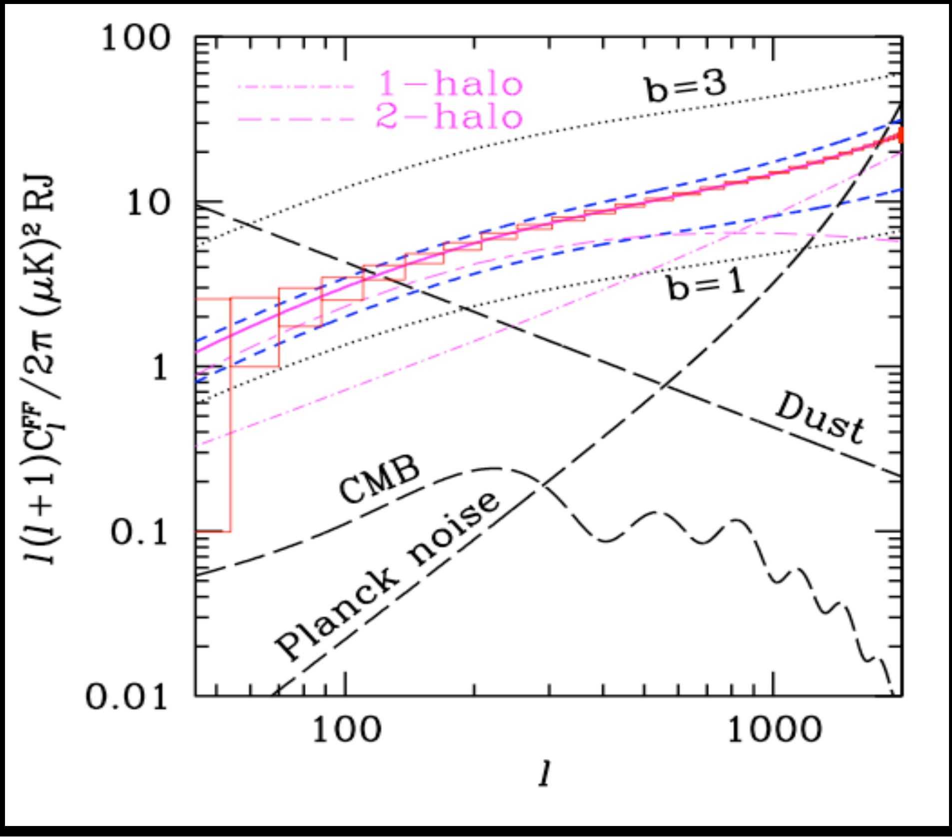
Joint studies with CMB: *Search for large-scale structure responsible for lensing the CMB*



Joint Studies with CMB







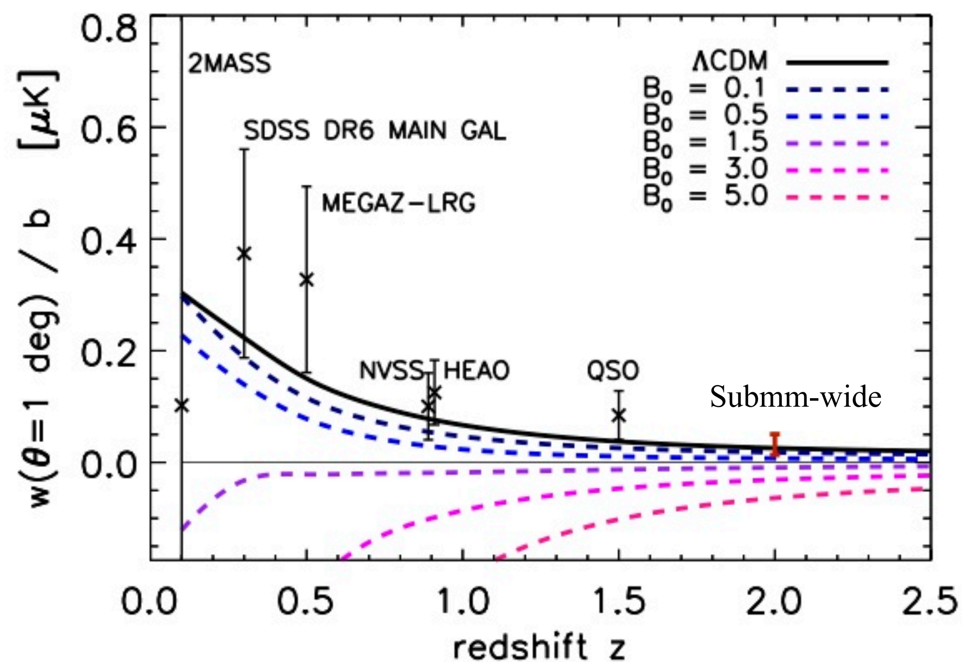
CMB lensing-CIB predictions: Song, Cooray, Knox & Zaldarriaga 2003

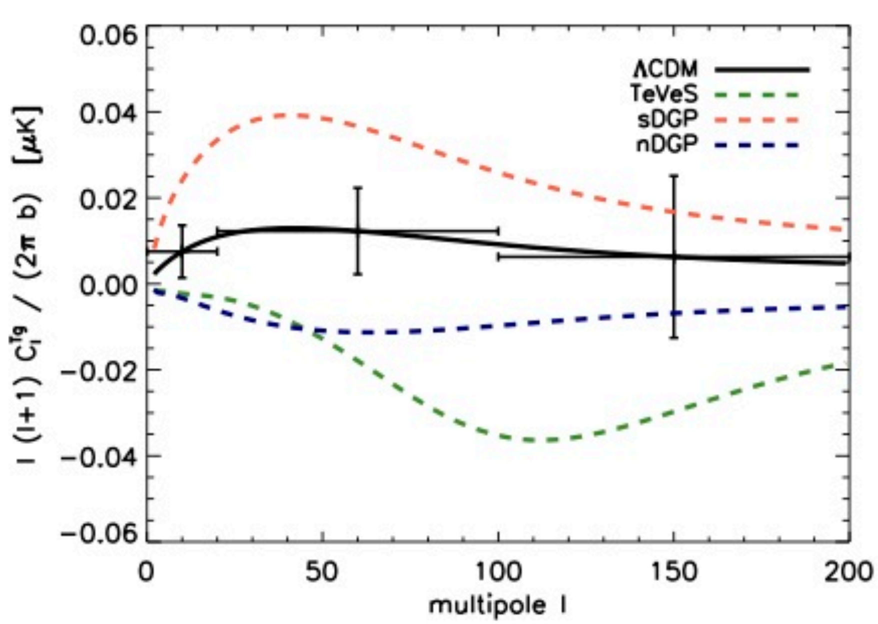
SMGs are better correlated with CMB lensing than optical surveys. SMG-wide survey can identify structure that is responsible for lensing of the CMB.

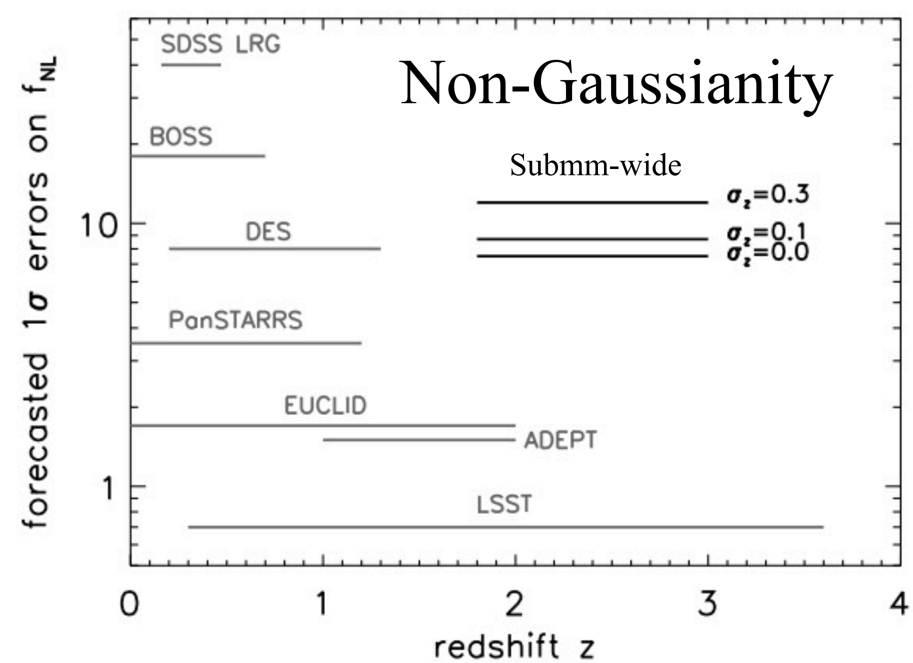
[Clear from tons of CIB X CMB-lensing papers over the last three years]

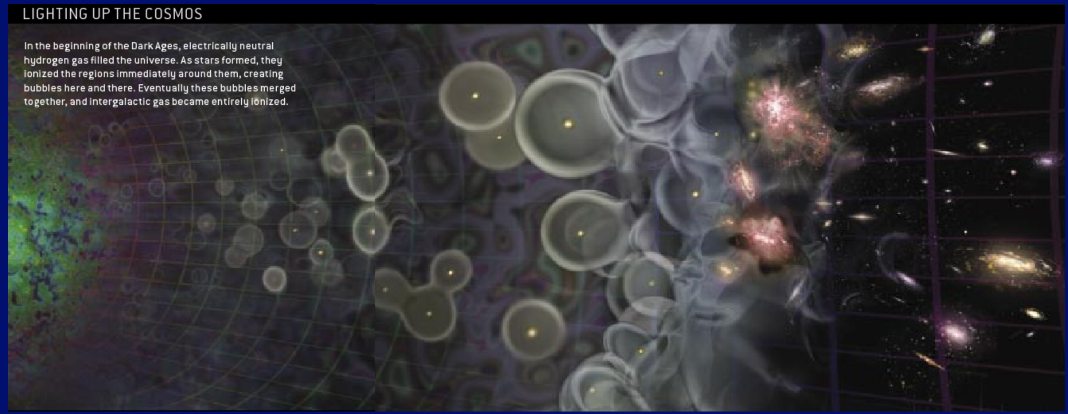
z~2 ISW with Planck+Sub-mm wide

A strong probe of modified gravity theories for acceleration (need > 1000 sq. degs)









CO probe based on

Yan Gong, Asantha Cooray, Marta Silva, Mario Santos, Philip Lubin

Probing Reionization with Intensity Mapping of Molecular and Fine Structure Lines

Astrophysical Journal Letters, 728, L46-L51 (2011).

(see also Chris Carilli, arxiv.org:1102.0745; Lidz et al. arxiv.org:1104.4800)

CII probe based on

Yan Gong, Asantha Cooray, Marta Silva, Mario Santos, Jamie Bock, Matt Bradford, Mike Zemcov

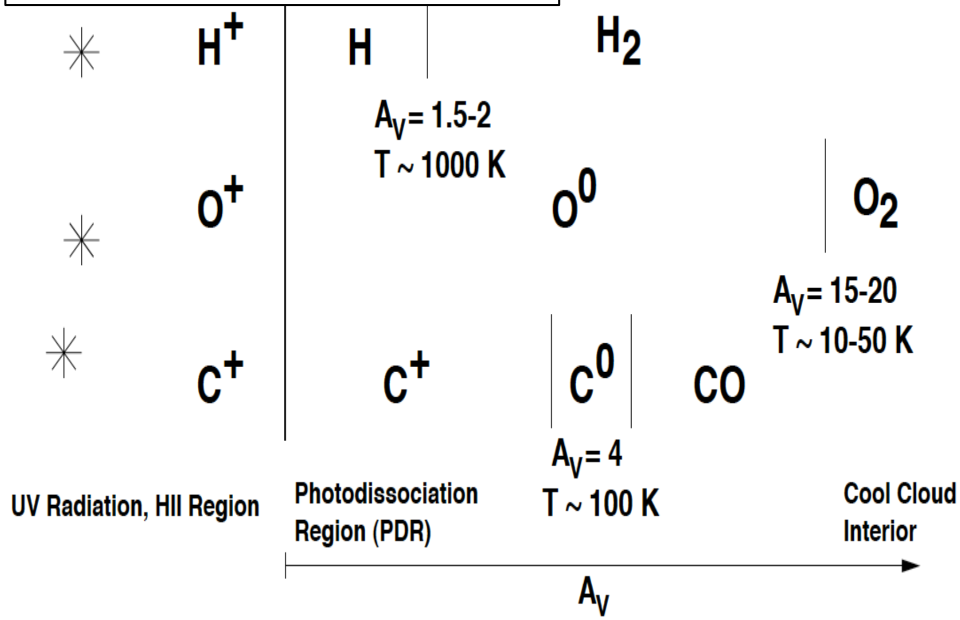
Intensity Mapping of the [CII] Fine Structure Line During The Epoch of Reionization

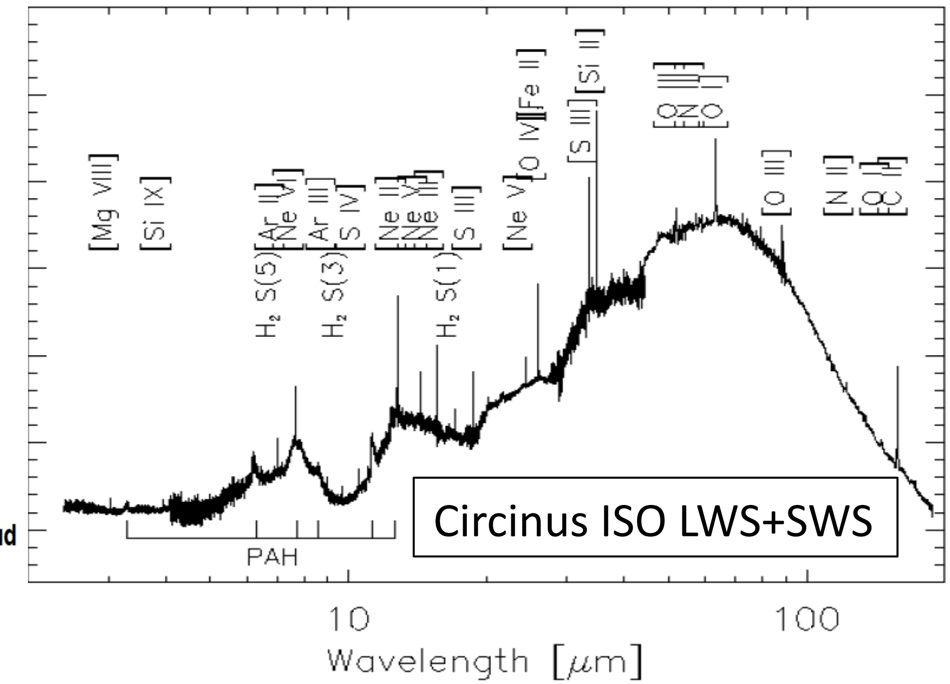
ApJ 2011, arxiv.org:1107.3553

Atomic and Molecular Lines as a Probe of Reionization

C+ and fine-structure lines in galaxies

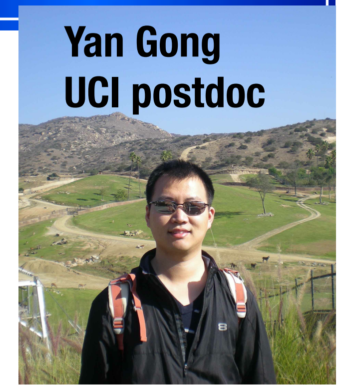
Photodissociation region





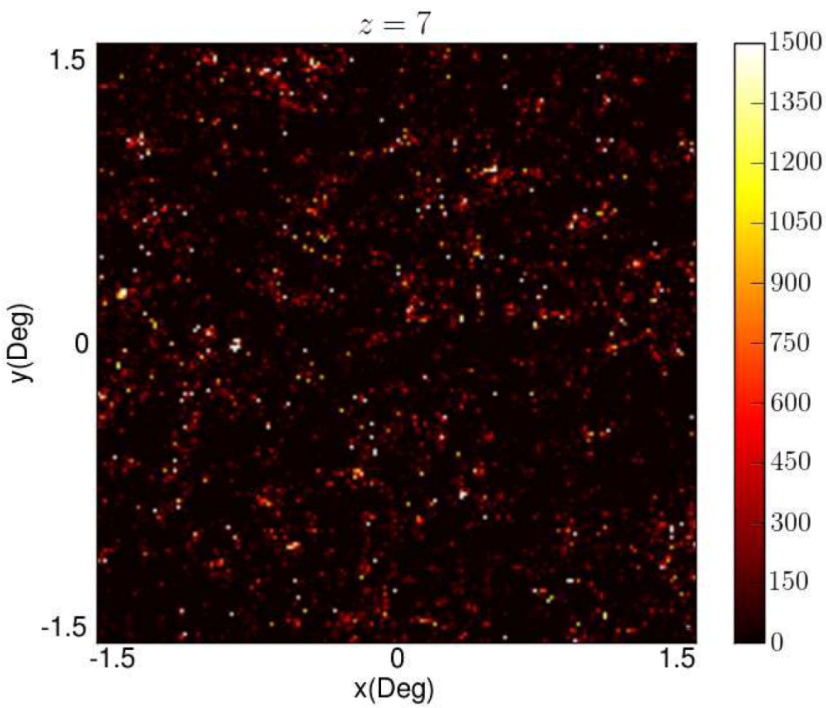
- C+ ionization potential 11.6 eV, so it exists in neutral gas where much of the energy is input into the interstellar medium.
  - Easily thermalized with a critical density of 3e3 H_2 cm^{-3} or ~50 e^- cm^{-3}
  - Dense photo-dissociation regions: regions, C-ionizing photon density is set by dust extinction
    - C+ carries a large fraction of the gas cooling (30-50%, (of the 1% of the total))
  - Among the most luminous spectral line in the spectra of galaxies.
    - -> less dust to gas means more C+.
- Also traces diffuse ionized gas.

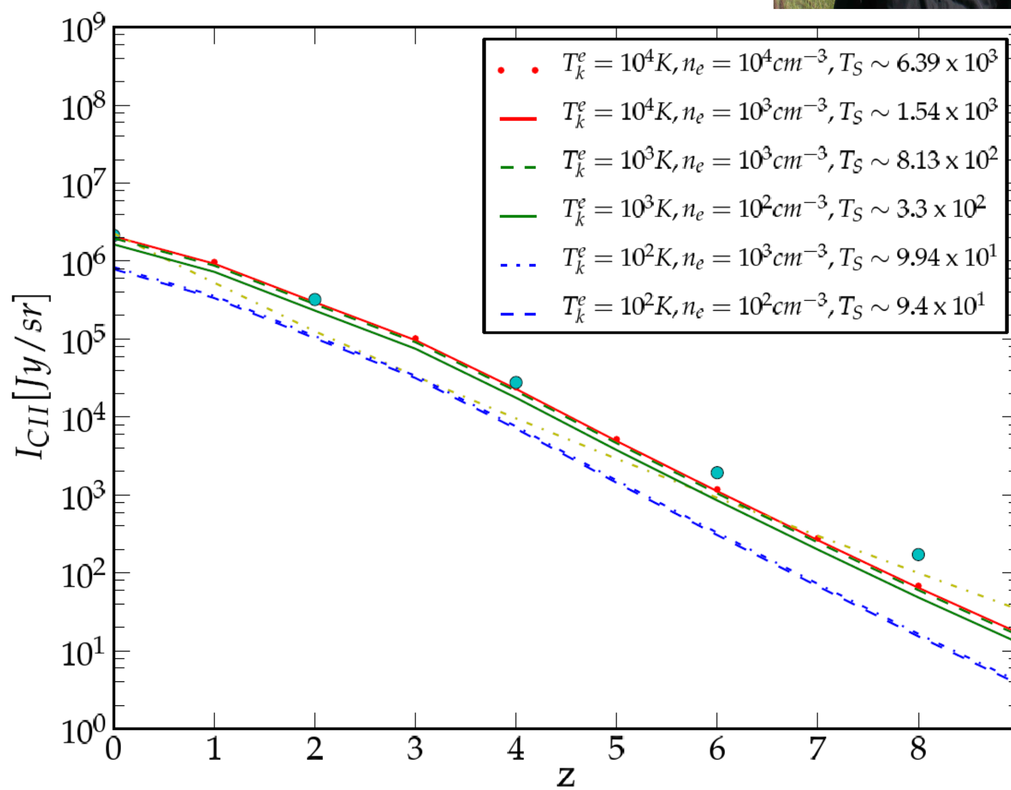
[CII] Expectations



- [CII] serves as a tracer of star formation
- The clustering signal traces total luminosity
  - -> unlike a flux-limited galaxy survey
- Use [CII] to spatially trace SF during the reionization epoch

Simulated Sky in [CII]





Gong, Cooray et al. 2012, ApJ 745, 49G

Table 2: TIME-*Pilot* Experiment Parameters

Number of spectrometers	32: 16 each pol, grid diplexed
Number of 150 GHz photometers	16, spectrally diplexed
Total # of detectors	1840: TES bolometers with SQUID MUX
Instantaneous FOV	11 arcmin × 0.35 arcmin (@ spectrometer mid-band)
Cryostat, base temperature	Existing 4K / 1K system with ^{3}He cooler at 250 mK.
C+ Survey volume (comoving)	153 Mpc × 0.85 Mpc × 1240 Mpc deep
C+ Survey on-sky integration time	240 hours, estimated
kSZ δv_{pec} sensitivity	$\pm 500\,\mathrm{km\ s^{-1}}$ per beam in 8 hours

Instrument Parameters

Parameter	Photometers	Grating LF Band	Grating HF Band
Spectral range [GHz]	135 – 165	183 – 230	230 – 326
Estimated end-to-end optical efficiency	0.3	0.3	0.3
# of Bolometers per sub-band	1	24 (8×3)	36 (12×3)
Atmospheric PWV monitor channels		10: 183 – 199 GHz	6: 305 – 326 GHz
$\nu/\delta\nu$ per detector	5	92 – 122	90 – 120
NEI on sky per detector [(MJy/sr)$\sqrt{\mathrm{sec}}$]	0.3	3.3 – 4.0	5.3 – 8.3
NEFD on sky per detector [mJy$\sqrt{\mathrm{sec}}$]	6	37 – 44	42 – 56
TES Bolometer Parameters			
TES safety factor (= $\mathrm{P_{elec}}$ / $\mathrm{P_{opt}}$)	3	3–5	5–8
Detector + MUX NEP [$10^{-18}\,\mathrm{W\,Hz^{-1/2}}$]	40	9.7	13
Photon NEP [$10^{-18}\,\mathrm{W\,Hz^{-1/2}}$]	60	14 – 17	16 – 24
Absorber size [mm]	ϕ 4.0	3.0 × 3.48	3.0 × 2.32

Caltech Keck Institute funds + NSF-ATI proposal pending for full construction going to JCMT through Taiwan time

TIME: Tomographic Ionized-Carbon Mapping Experiment

TIME Team

Caltech / JPL

Jet Propulsion Laboratory
California Institute of Technology

- Jamie Bock
- Matt Bradford
- Zak Staniszewski
- Abby Crites
- Steve Hailey-Dunsheath
- Mike Zemcov
- Roger O'Brient
- Bade Uzgil (UPenn)
- Corwin Shiu
- Jonathon Hunacek

UC Irvine

- Asantha Cooray
- Yan Gong
- Chang Feng

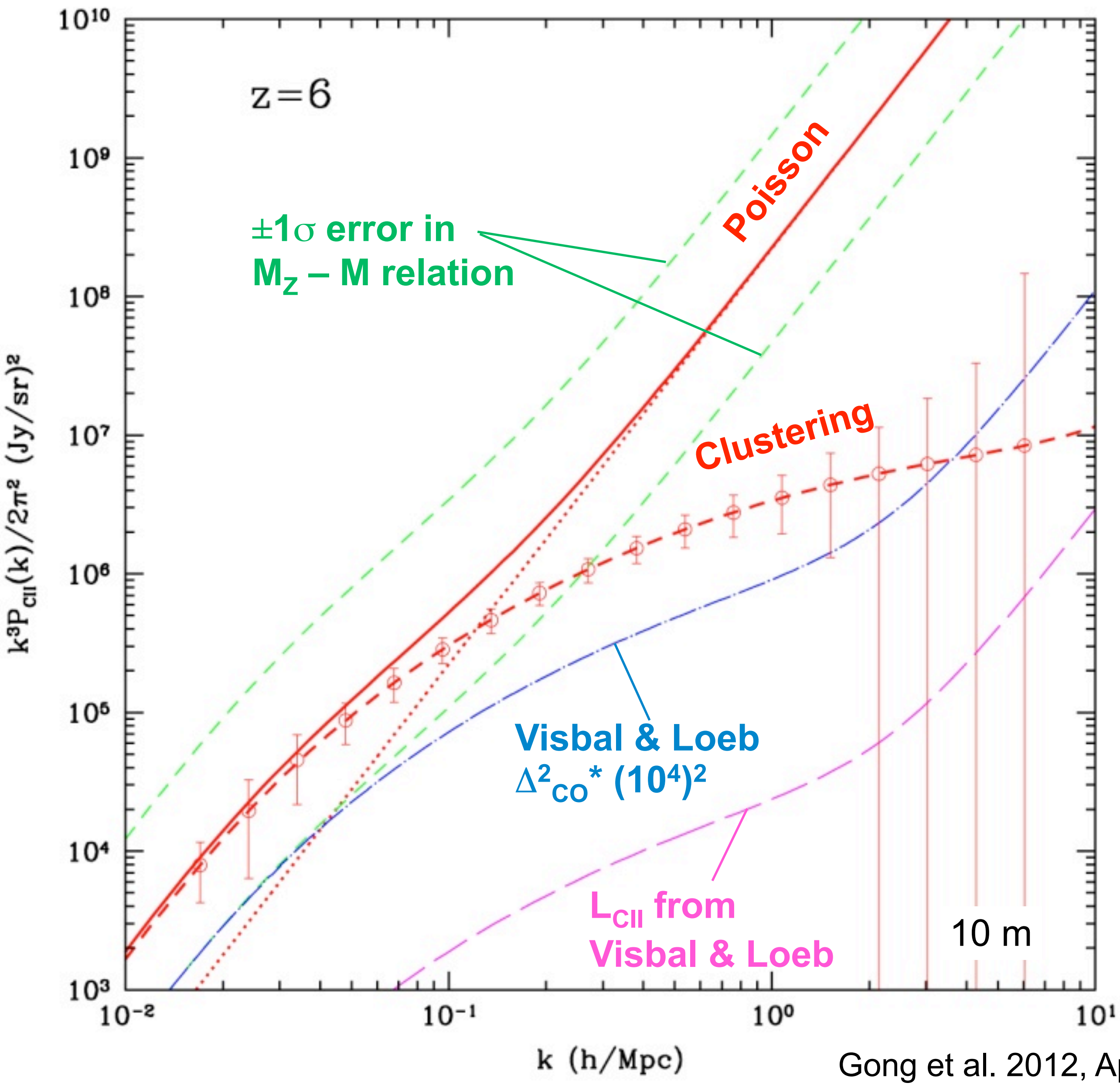
ASIAA

- Tzu-Ching Chang
- Chao-Te Li
- Patrick Koch

Chicago

- Erik Shirokoff

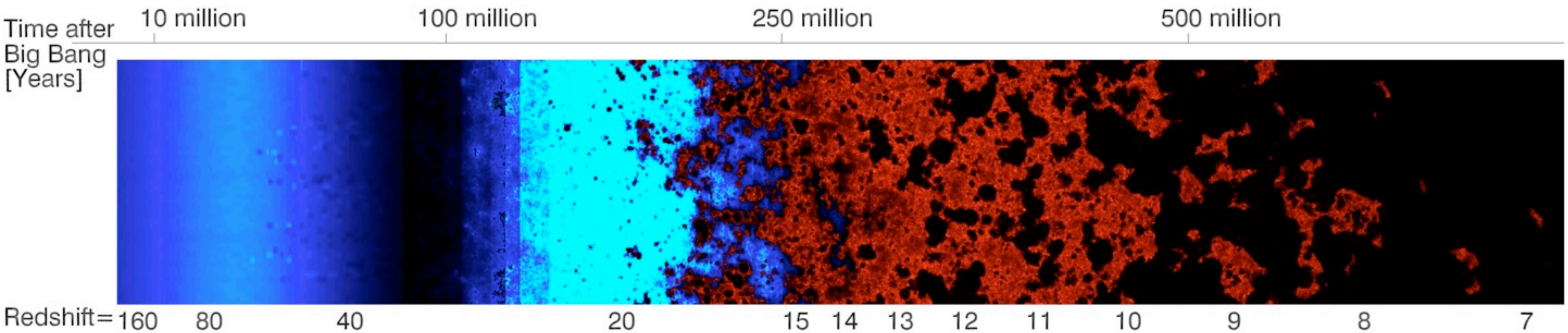
TIME-*Full* [CII] Sensitivity Predictions

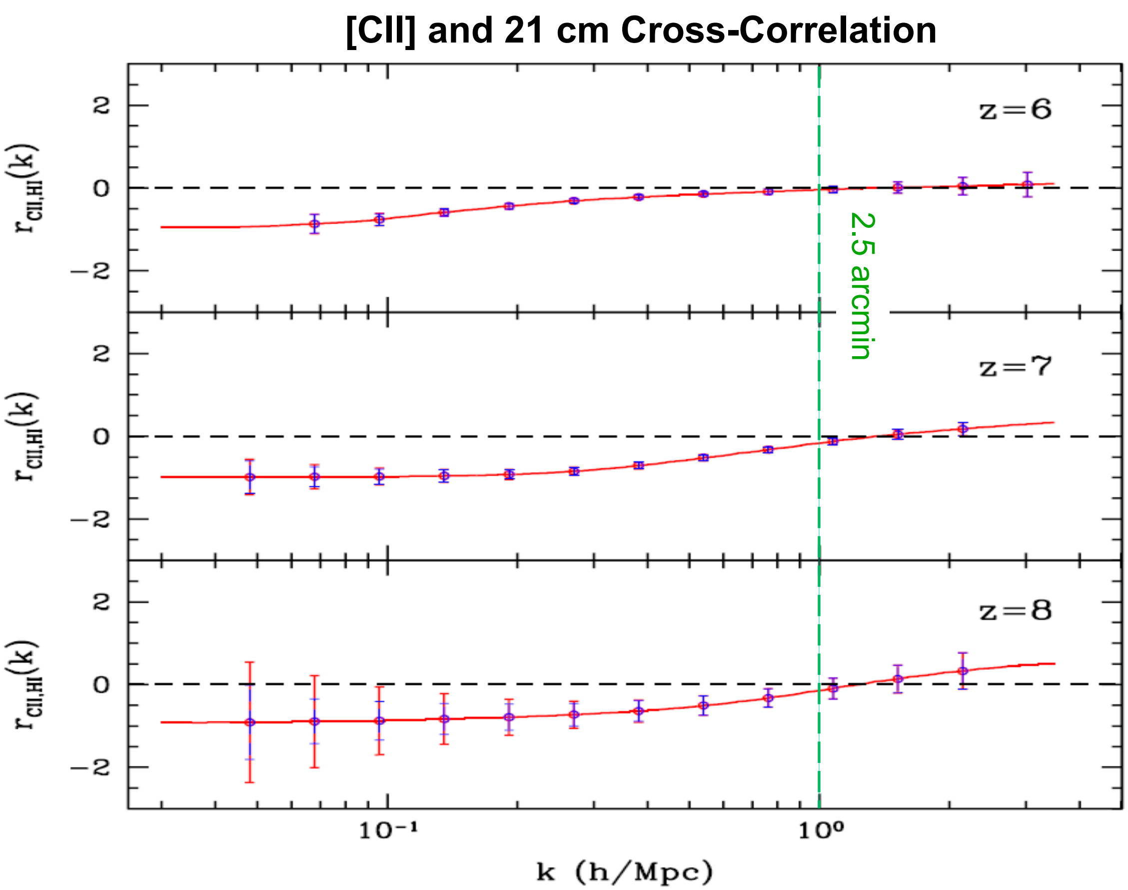


Lidz *et al*. 2011
Δ^2_{CO}*4000^2
agrees with
Gong C+ model
at z = 7

Gong et al. 2012, ApJ 745, 49G

Using 21 cm & [CII] Together



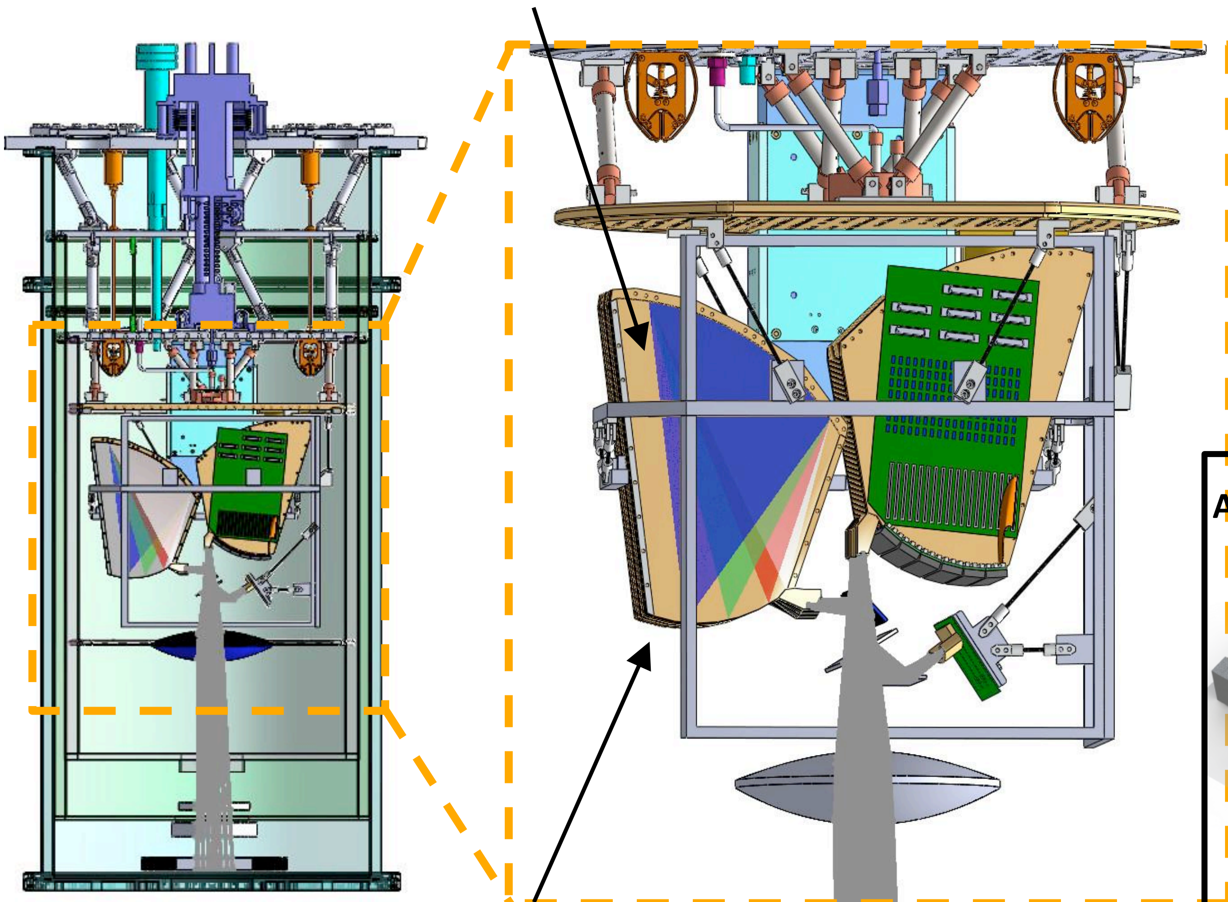


- Star formation rate vs. z
- Ionization state vs. z
- Bubble size

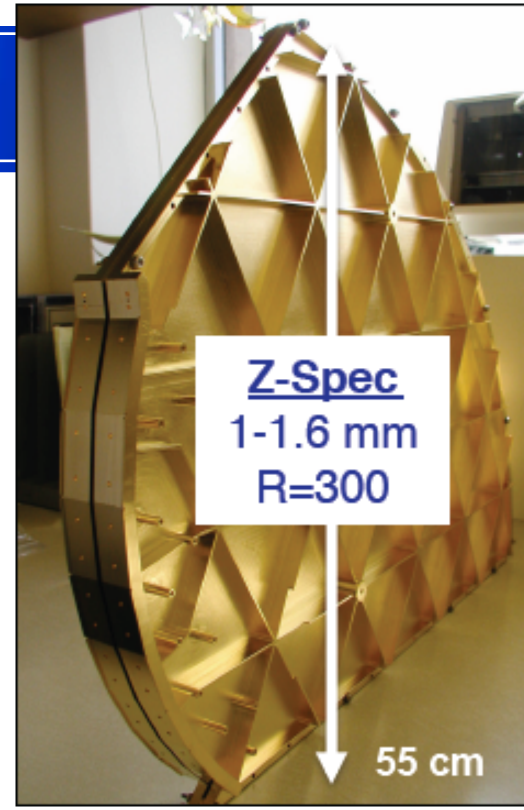
Gong et al. 2012, ApJ 745, 49G

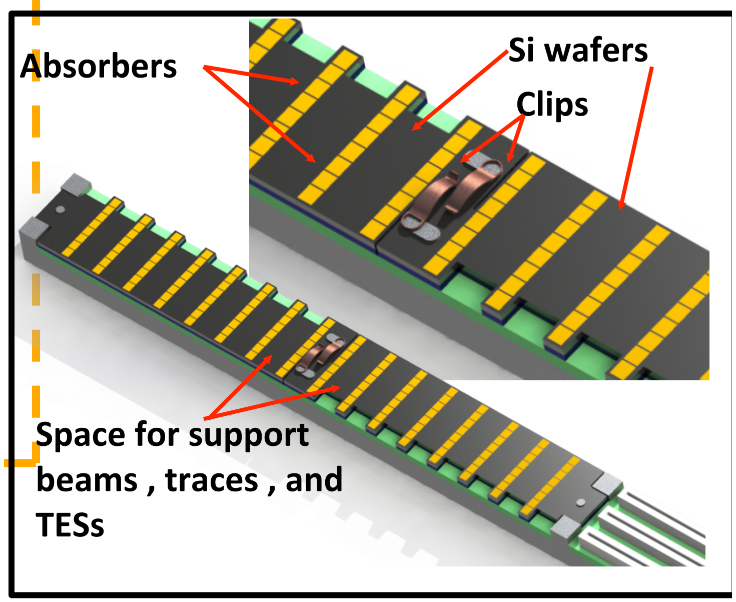
TIME-*Pilot* Design

16 grating spectrometers for each polarization (R~100,183-326 GHz)

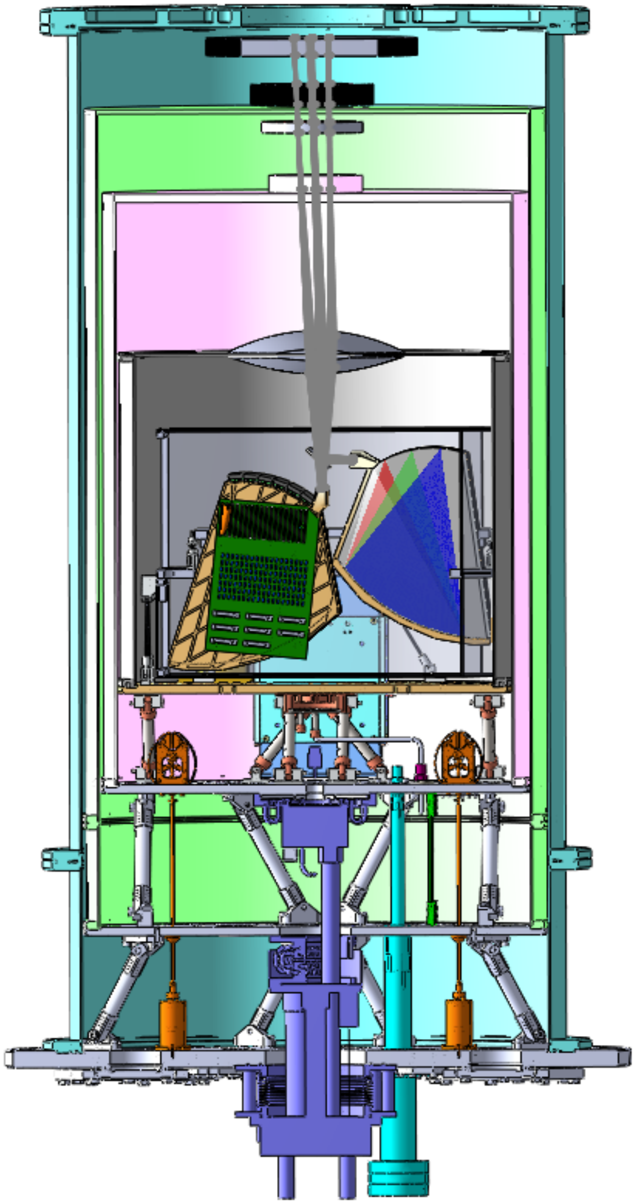


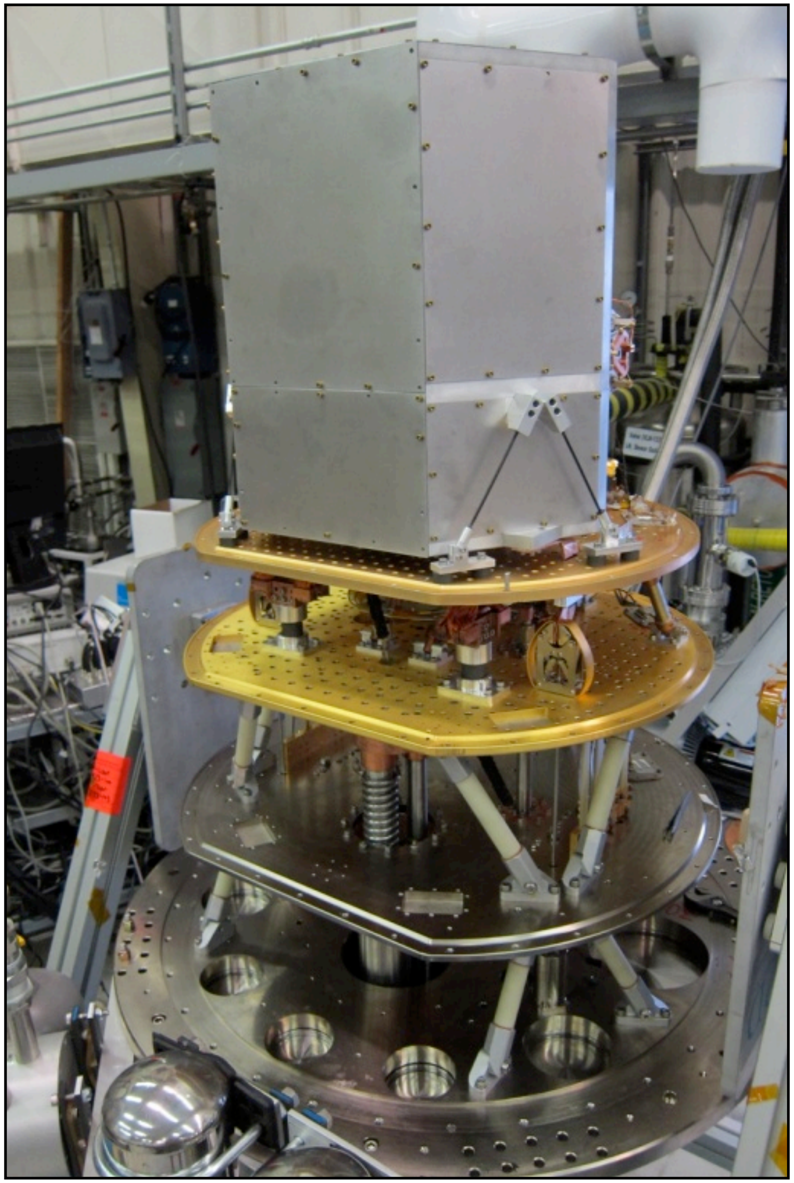
60 TES bolometers per spectrometer (1840 total)





TIME-*Pilot* Moving Forward

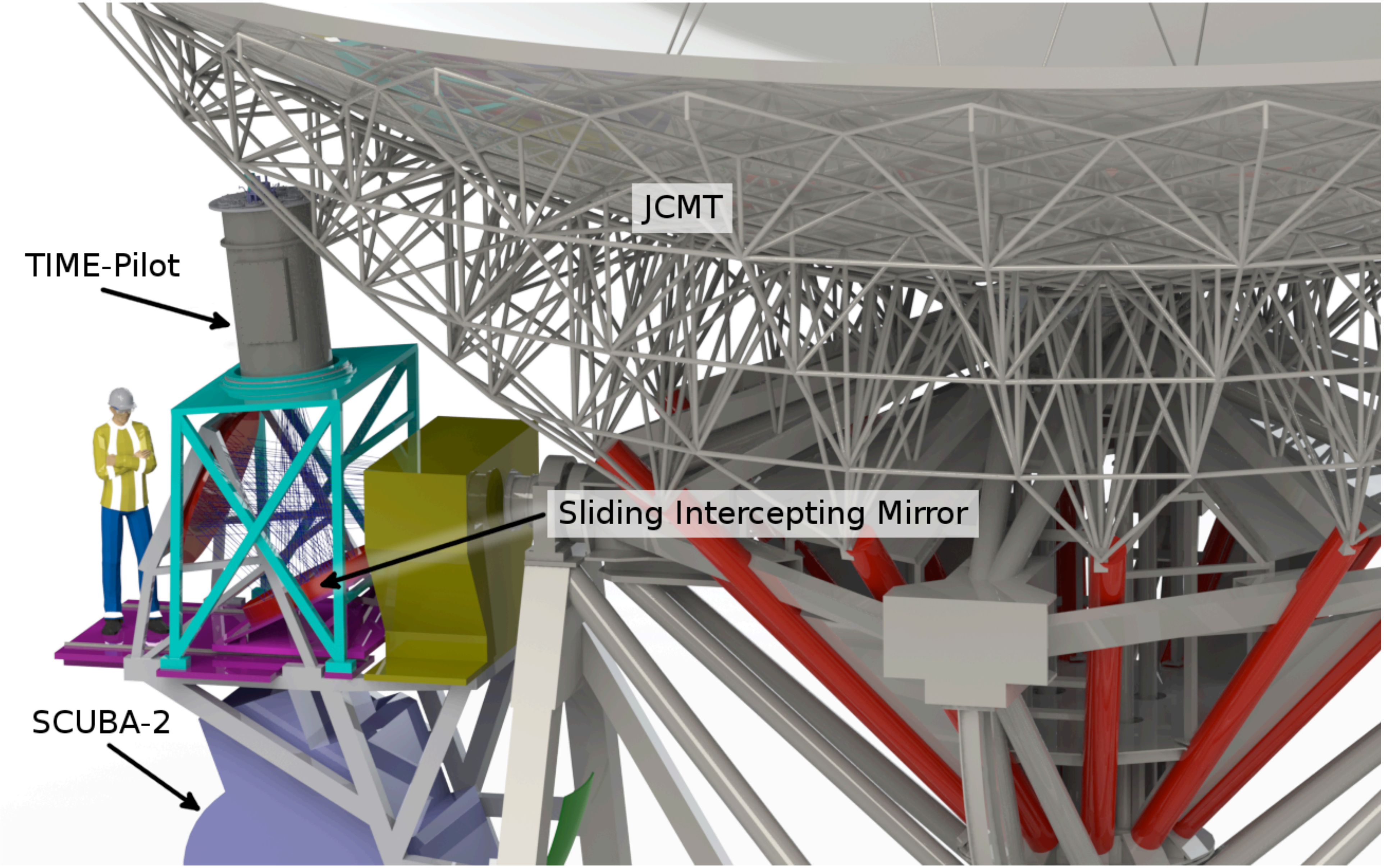




TIME-*Pilot* Location

- Planned for JCMT, a 15 meter sub-millimeter telescope on Mauna Kea in Hawaii
- Time through ASIAA, which bought telescope through an East Asia Consortium

TIME-*Pilot* Location



TIME-*Pilot* Survey

- 11 x 0.35 arcminute instantaneous FOV (16 x 1 beams)
- Total survey 156 x 1 beams (1.0° x 0.35')
- Line scan minimizes map area to minimize noise given fixed integration time
- Estimated 240 hours on the sky

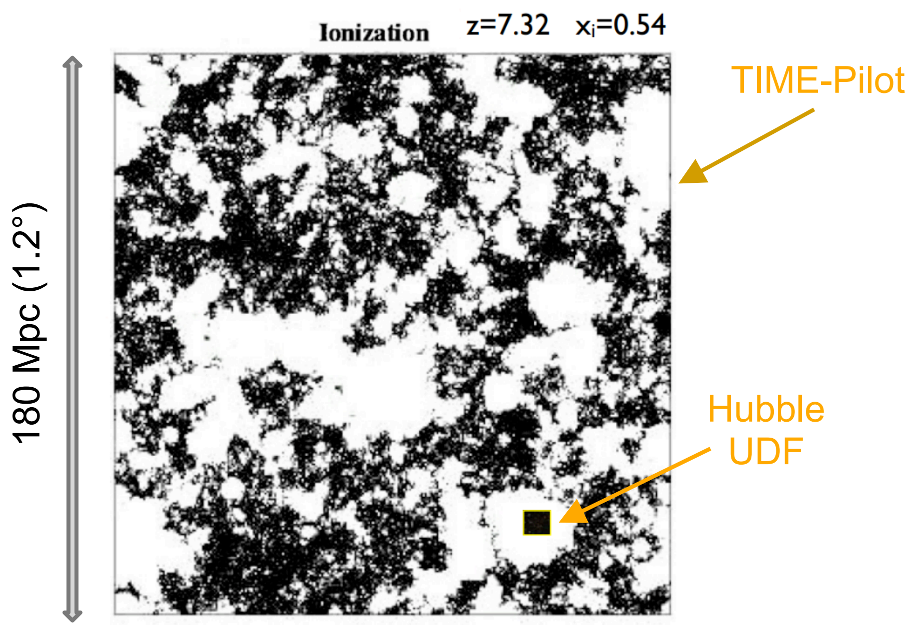
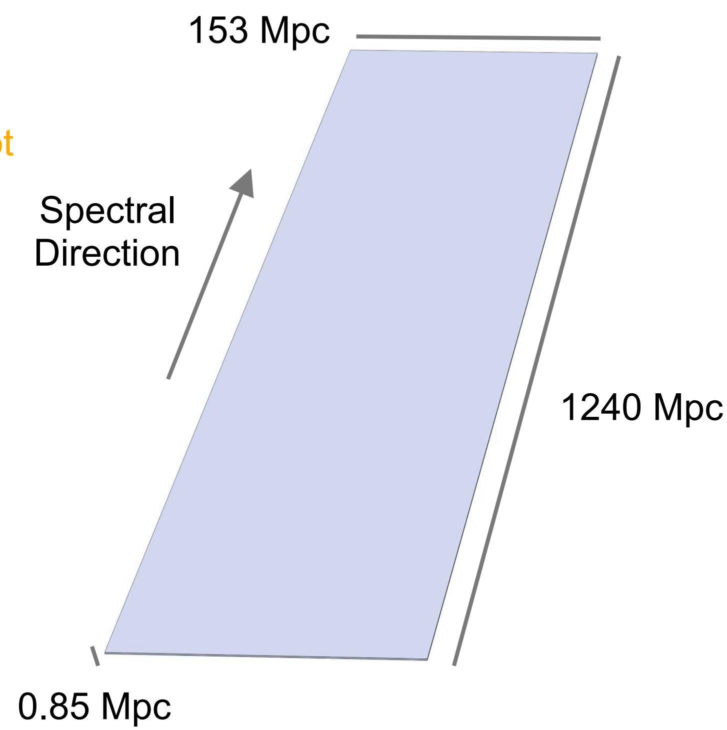


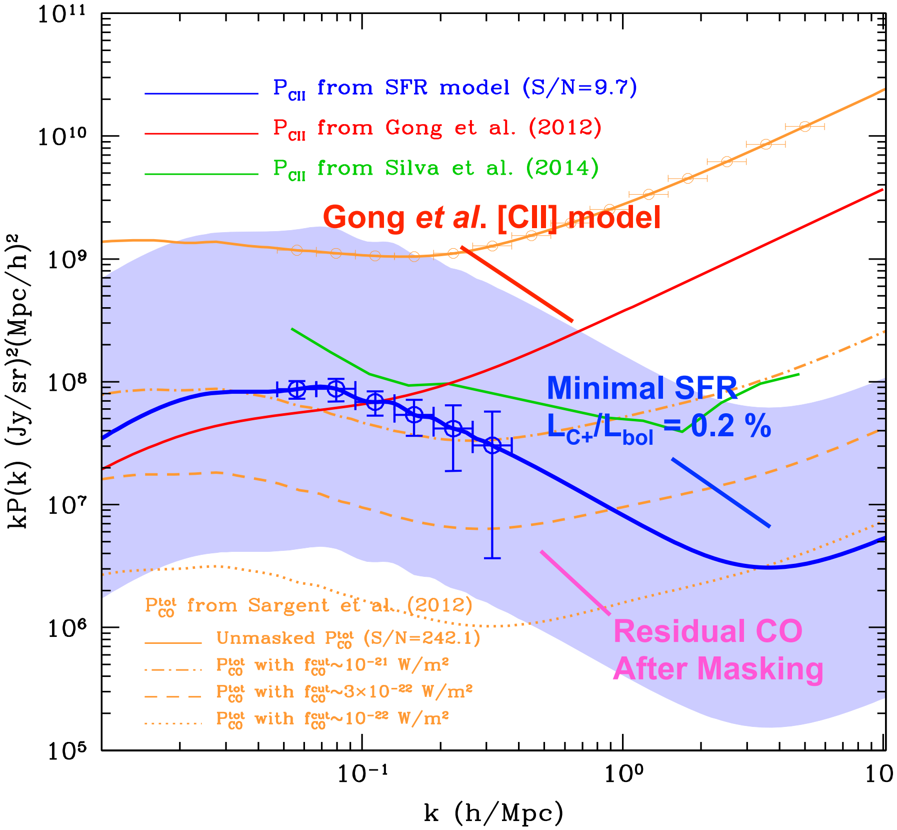
Figure from Lidz et al., 2009, Modified by Pritchard

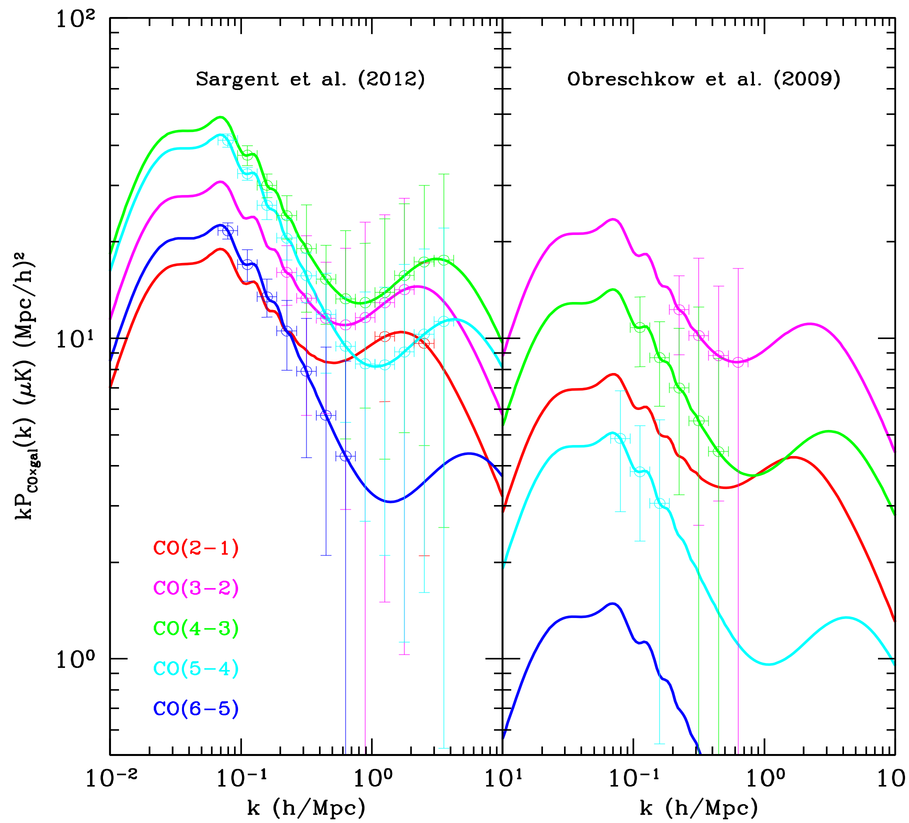


First Detections with TIME-*Pilot*

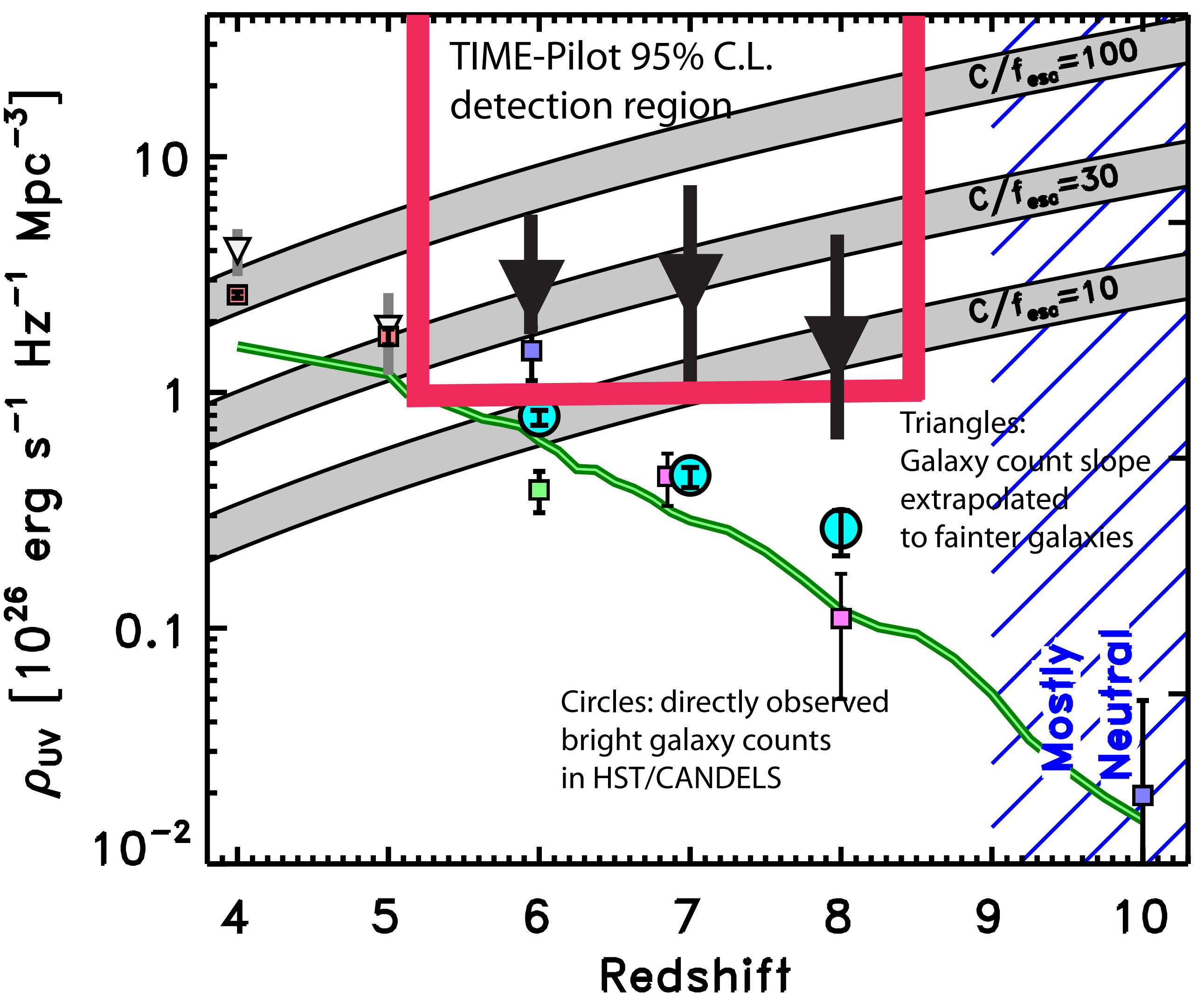
Epoch of Reionization Science
- Detect [CII] clustering
- Detect [CII] Poisson fluctuations
- Discriminate between models

Ancillary Science
- CO clustering fluctuations
- Assess residual CO foreground
- Powerful kSZ instrument



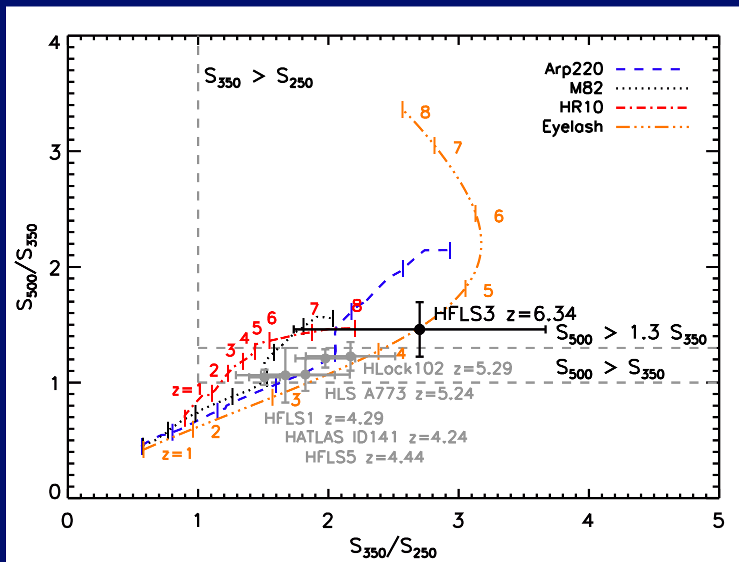


A first detection of [CII] fluctuations justifies full EOR mapping measurements

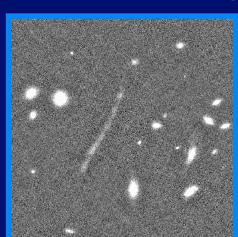


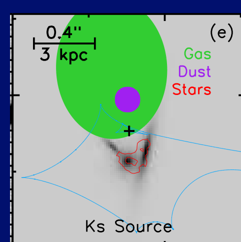
TIME: Tomographic Ionized-Carbon Mapping Experiment

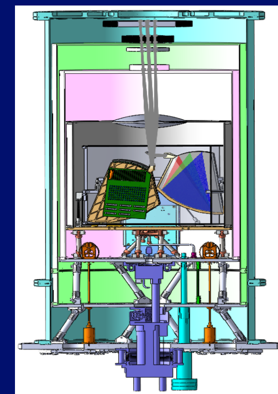
Dusty, starbursts are not limited to z~2
(Riechers et al 13 Nature;
also results from SPT team)

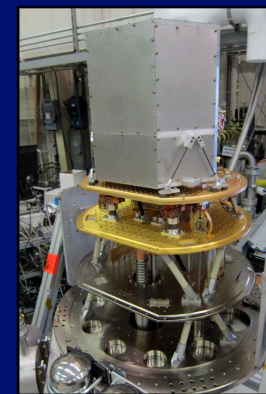


Extensive followup programs, currently on bright lensed and rare SMGs, are providing a detailed view of high-z star-formation, the relative distribution of gas, dust, and stars.









TIME-Pilot making progress. Awaiting NSF funds for instrument completion by the end of 2016. 2017 observations start.

For an extensive review of dusty, star forming galaxies see
Casey, Narayanan & Cooray (2014)
Physics Reports in press 1402.1456

Summary

THIS TALK AVAILABLE AT HERSCHEL.UCI.EDU